Master's Thesis

# DESIGN FOR ADDITIVE MANUFACTURING (DfAM) OF LARGE SIZE PRODUCTS USING A PLASTIC PELLET EXTRUSION: CASE STUDY OF THE EXCAVATOR CABIN PRODUCTION

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## Abstract

In recent decades, additive manufacturing has begun to impact real industry through significant growth. As the reliability of the final product using AM became higher, the cases applied to the actual production began to appear. In addition, as DfAM, a methodology for understanding the characteristics of AM and exploiting its advantages, has emerged, products with high functionality have been produced without penalties of cost and time. However, there are many problem that should be solved ultimately in order to be utilized in the real industry. Generally, AM is that it requires a closed space for the process and size of final part determined by AM machine. Products with more than size of unit meter are difficult to make with regular AM equipment. In order to make a large sized-products, at the design stage, additional processes are needed to fragment the original part, and is added assembly process. It can also take few hours to several days to build up a fully part located batch of AM. Therefore, AM technology needs a solution to rapidly produce large-sized products that are being produced in the real industry. As presented in this research, Large Object Additive Manufacturing (LOAM) can be a solution to this problem. Large Object Additive Manufacturing can stack several kilograms of material per hour on a large bed with meter units.

This paper describes a large object additive manufacturing method, which is a feasible method for making large sized-products with fast fabricating speed. And propose a method to apply LOAM to DfAM which is a design technique that takes maximum advantage of 3D printer. In addition, a case study demonstrates the method of manufacturing the actual industrial excavator cabin using LOAM. A prototyping plan for the 3D printed excavator cabin is described and a design method is proposed to secure the structural safety through the topology optimization method. Adjustment methods are explained to produce successful 3D printing results. In this paper also explains how to assemble large parts made of polymers. Finally, 3D printed excavator cabin project is summarized to the AM methodology of large products through DfAM. Furthermore, establish methodology of applying DfAM technology for creating new products.

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# 1. Introduction

## 1.1 Background

AM technology has grown steadily over the last few years and has become an important area of industry with continuous development. In addition to increasing personnel 3D printers, industries that demand high-quality end production such as automotive, aerospace, and medical applications are increasingly using AM. Global Additive Manufacturing companies are increasing their investment Research and Development to become competitive. Large AM companies such as Stratasys, Materialize, and 3D Systems have invested $138 million in R&D over the past three years [1]. AM companies are striving for technological development through partnerships among global companies in other fields. General Electric (GE) is the world's largest global infrastructure company with operations in power, aviation, healthcare and transportation. Mohammad Ehteshami, vice president for additive integration at GE Additive said, "ARCAM AB and Concept Laser are important players in the growing additive manufacturing movement and are foundational to GE's journey into this revolutionary manufacturing space." Finally, GE acquired ARCAM AB, a leader in metal AM, and Concept laser in 2017 [2]. The automotive industry is also actively investing in AM technology. Leading automotive companies such as General Motors, BMW, Audi and Volkswagen have partnered with AM companies and are concentrating on technology development through large capital investments.

The Wohlers Report publishes reviews and analysis data centered on the AM industry every year. The Wohlers report's Product and Service profits of AM analysis shows a very large growth rate. In 2017, AM products showed an increase of 17.4%, Systems upgrades showed an increase of 14.8% and AM services showed an increase of 23.8% from the previous year in 2016. According to the Wohlers report, the AM industry has grown considerably over the past eight years and the market has grown 5.5 times over this period [3].

There is an exact definition of Additive Manufacturing definition given in the ISO/ASTM 52900 standard. Additive manufacturing is the "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing methodologies" [4]. Conventional manufacturing processes require a larger base material than the originally intended design model data. This is because conventional manufacturing is mostly the process of shaving base material using rotating tools such as spindles. In addition, the designer should input all information such as dimensions, angles of designing models and match all information in three dimensions space. That is, the designer must specify the geometry of parts in detail. On the other hand, Additive manufacturing is a method of direct fabrication from 3D CAD (three-dimensional computer-aided design) data by layering, and AM software usually uses STL files which contain the surface geometry information of the object in actual production. In conclusion, knowing 3D CAD data, material information, and characteristics of 3D printing equipment to be used, AM can be a solution to simplify the process and to utilize resources efficiently [5].

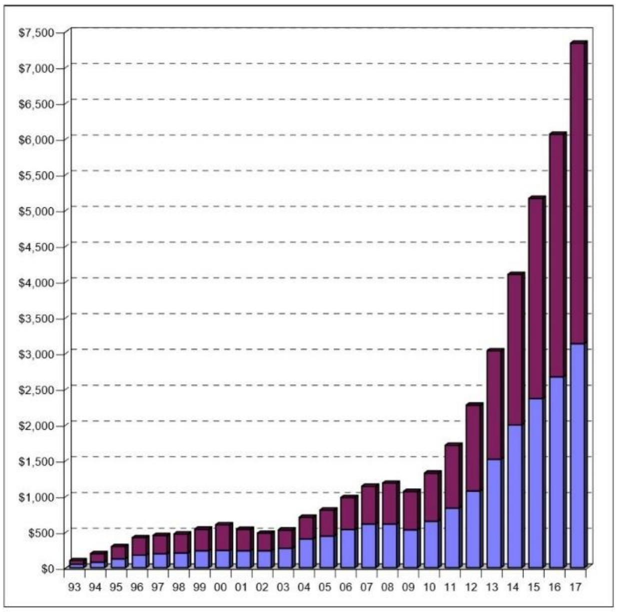



**Figure 1 AM products and Service Profits**

Nowadays, it seems to be hard to make that additive manufacturing replace recent conventional manufacturing for producing in large quantities. For example, traditional injection-molding processes can produce thousands of products in one hour. On the other hand, if you have ever used a 3D printer, you can see that the AM process takes a lot of time. Though emerging as an innovation in manufacturing, AM has always been pointed at the slower molding speeds due to manufacturing size and geometric complexity that are not available in the industry, as well as high production costs.

But we have to wonder why today’s conventional manufacturing has evolved. Development of machines was required to make better products, and a large amount of capital was invested. Of course, the price of the first machine was very expensive. However, as the demand for machines increases and the supply increases, mass production systems using the conventional manufacturing process becomes possible.

Compared to conventional manufacturing, AM certainly has economic disadvantages. However, additive manufacturing has two major advantages that conventional manufacturing cannot achieve. First, it has freedom of design complexity. AM is able to create new and different types of designs as tool limitations are much less than conventional manufacturing. This is the basis for a new design technique called Design for Additive Manufacturing (DfAM). DfAM is a technique that provides a solution to overcome the process limitations encountered in the existing design and manufacturing process. It refers to the additive manufacturing technique that takes advantage of the characteristics of the AM equipment and makes full use of its advantages. This makes it possible to easily produce a product with a complicated shape structure through AM. Second, the production step can be placed in the planning step. These advantages are individually utilized for each product that the user desires and design modification can be performed in a wide range to meet the needs. For these reasons, additive manufacturing is a powerful advanced technology, and most industries are dramatically changing by adopting additive manufacturing technology.

In addition, the points that appealed to the disadvantages of AM became a motivation to develop AM technology. Lack of productivity regarding industrial applications has become another point of view for AM, and it has become a stepping stone for development. The AM field, which has been creating and researching products of a small volume for decades, has undergone recent upheaval. A method for producing large-sized products called “Large Object Additive Manufacturing or Big Area Additive Manufacturing” has emerged, and the products of this innovative method are already being applied to real industries. In the field of automotive, there are cases where all the parts except for the power train are made into large-object 3D printers and are used in real life. In the field of Aerospace, large object 3D printers are used for weight reduction of fuselage, wings and internal support. In the end, additive manufacturing was bigger and stronger than ever before as AM developed what it thought were limitations.

## 1.2 Objectives

Large Object Additive Manufacturing is a suitable method for large-size structures and the deposition speed is much faster than other different types of additive manufacturing technologies. Therefore, LOAM is capable of rapid prototyping based on fast laminating speed even if the build size is as large as a unit meter. Currently, the market for finished products using additive manufacturing is also rapidly increasing, and many attempts have been made in various industries to apply them to real industries. However, there are negative views that additive manufacturing can ultimately change the current production system in order to be used in the real industry. This is because additive manufacturing has been active in the development of algorithms for dimensional correction or thermal deformation centering on high-quality end production for objects with small volumes for decades. Ultimately, however, in order to positively introduce AM into the industry, the manufacturing and production speed of large structures that can be incorporated into the current manufacturing methods must be considered. In addition, it is also important to apply new materials in order to actually use them in industry, and it is necessary to find optimal solutions through fusion with conventional manufacturing methods. At the current stream, ABS-CF is also used to enhance the mechanical properties of the composite material, and it is developing the final product quality through fusion with conventional manufacturing methods such as CNC.

In this paper, the author discusses applications and cases of actual Large Object Additive Manufacturing in industry and articles and examples of composite materials with sufficient mechanical properties for practical applications. Also observed are the characteristics through specimen testing which is used in actual Large Object Additive Manufacturing. In addition, it studies the characteristics of Large Object Additive Manufacturing and a methodology for applying DfAM. Based on this background knowledge, the main cabin part protecting the driver of the excavator is designed according to the DfAM process and manufactured using Large Object Additive Manufacturing. In conclusion, the above process is established as a method for the fabrication of large structures using DfAM, and the study aims at demonstrating the possibility of actually utilizing and introducing AM technology in industry.

# 2. Literature survey

## 2.1 Design for Additive Manufacturing

In order to effectively utilize one kind of manufacturing, its specific manufacturing capabilities and manufacturing constraints must be considered. The above process is defined as Design for Manufacturing (DfM). However, additive manufacturing has unique capabilities different from conventional manufacturing. Therefore, researches on Design for Additive Manufacturing began to understand AM and started to utilize the capabilities of AM. AM has a much higher degree of freedom than other manufacturing processes. For example, AM has design complexity or customized geometries, and is a suitable process for fabricating parts made of composite materials. According to Rosen, Design for Additive Manufacturing should "Maximize product performance through the synthesis of shapes, sizes, hierarchical structures, and material compositions, subject to the capabilities of AM technologies." The author defined the following unique capabilities of AM.

- Shape complexity: With high feasible geometry, it is possible to realize any design.
- Material complexity: It is possible to process multi-materials at a time.
- Hierarchical complexity: Hierarchical multiscale structures can be designed and fabricated from the microstructure through geometric mesostructure to part-scale macrostructure
- Functional complexity: AM can fully fabricate functional body parts at once.

In other words, AM can build complex designs with a high degree of freedom based on the stacking layering method, without directing any additional manufacturing processes such as molds, dies, and Jig & Fixtures. DfAM is a technique that provides a solution to overcome the process limitations encountered in the existing design and manufacturing process. It refers to the additive manufacturing technique that takes advantage of the characteristics of the AM equipment and makes full use of its advantages. The basic principles of DfAM are explained as follows.

- AM produces complexity design through integrating several features or multiple parts into one without wasting time or cost penalties.

▪ AM produces customized parts and specific features without changing the manufacturing process.

▪ In many cases, direct parts fabrication from Computer Aided-Design (CAD) without complex machining tools enables production to be economical.

▪ Using multi-materials and through considerate design of process, AM enables production of multi-functional part design and enhances the mechanical properties of parts.

According to Ponche et al., there are three steps of general DfAM methodology that consider the manufacturing process while maximizing part functionality. First, there is part orientation. This is the process of AM selection considering the surface finish requirements and dimensional accuracy of the part. Second, there is functional optimization. The authors suggest topology optimization to create optimal parts considering the manufacturing process and materials. Third, there is manufacturing paths optimization. This is minimizing costs and time while maintaining part functionality and mechanical properties through toolpath optimization in AM processes [6].

The AM process has unique capabilities that are different from conventional manufacturing, and DfAM has emerged as a new process for understanding the AM process and deriving its advantages. DfAM is an additive manufacturing methodology for understanding several characteristics of AM and positively implementing the functionality of the structure without cost and time penalties for complex geometry. Figure 2 shows a step-by-step process for DfAM [7, 8].

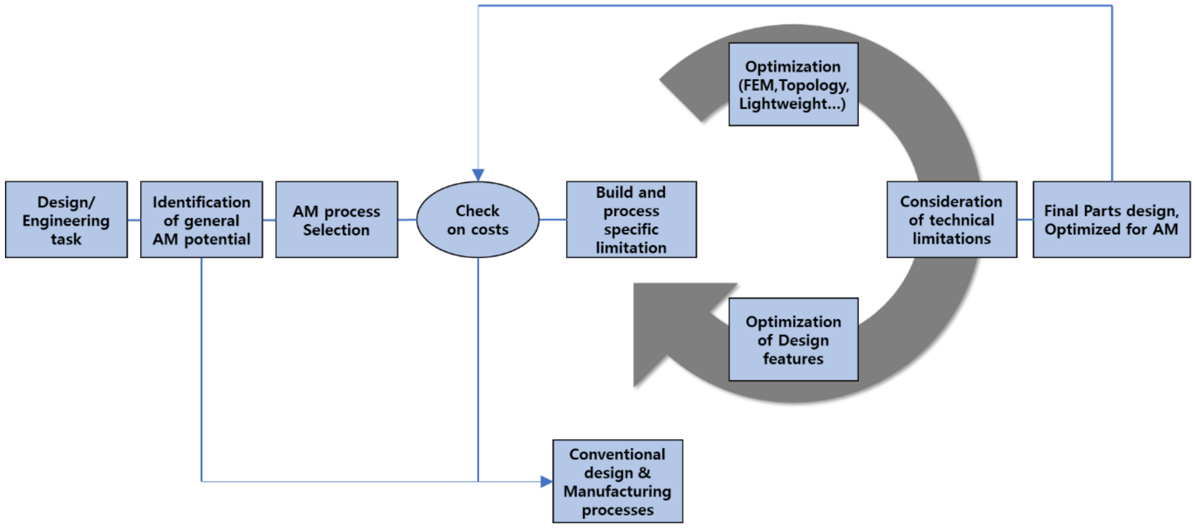



**Figure 2 Steps of Designing for Additive Manufacturing Process**

## 2.2 Topology Optimization in DFAM

DfAM uses optimization techniques to understand and utilize the benefits of the AM process. Topology optimization in functional optimization is mentioned in the three steps of DfAM methodology. Topology optimization is one of the methods that belongs to AM-related structure design optimization. AM-related structure design optimization methods are classified by optimization for stiffness and strength, compliance, manufacturability and so on. In predicting the results of the optimization methods, they are classified into two groups. If the optimization result is predictable, it is called positive optimization. If it is unpredictable, it is called passive optimization. Passive optimization includes shape optimization, size optimization and topology optimization [9].

According to Rosen, the capabilities of the AM process can lead to maximizing the performance of their designs while reducing their weight. In order to achieve the goal of maximizing the performance designs while keeping under constraints, it is called 'design for functionality' to perform a mathematically defined optimization method in the design space. The authors explain that size optimization, shape optimization, and topology optimization are important optimization methods included in AM [7].

In conclusion, a topology optimization method is to place material within the design space to achieve maximum structural performance. It also refers to using a mathematical method to minimize material used while maintaining specific loading and boundary constraints. For example, part volume is minimized by constraints such as stress, compliance, strain energy and possibly additional considerations [7, 10].

Topology optimization is an optimization technique that relocates the materials within the design domain while satisfying the given constraints. There is a basic equation of topology optimization

**Minimize** $C(\boldsymbol{\rho})$;

**Subject to** $V = \sum \rho_i v_i \leq V$

**Where** $\eta \leq \rho_i \leq 1$ , $\quad i = 1, \ldots\ldots, n$

$C$ : compliance (Constant indicating degree of structure strain)

$V$ : Target volume

$n$ : Total number of elements

$\rho_i$ : Density

$\nu_i$ : Volume

$\eta$ : Positive constant to avoid computational outliers

What is important here is the target volume which can be adjusted by designer and derive the result. In the project of this paper, topology optimization was done in a way that minimizes the compliance. Since the calculation of material density in design space is the main purpose, analysis is performed that minimizes compliance by considering only the direction of load [11]. There is a commercial software including topology optimization tool. Inspire 2018 of SolidThinking can make generative shape design through optimization results. Figure 3 is shown Inspire's actual user interfaces and topology optimization settings for the cabin project. In this case, optimization was conducted to maximize stiffness and 30 % of total design space volume.

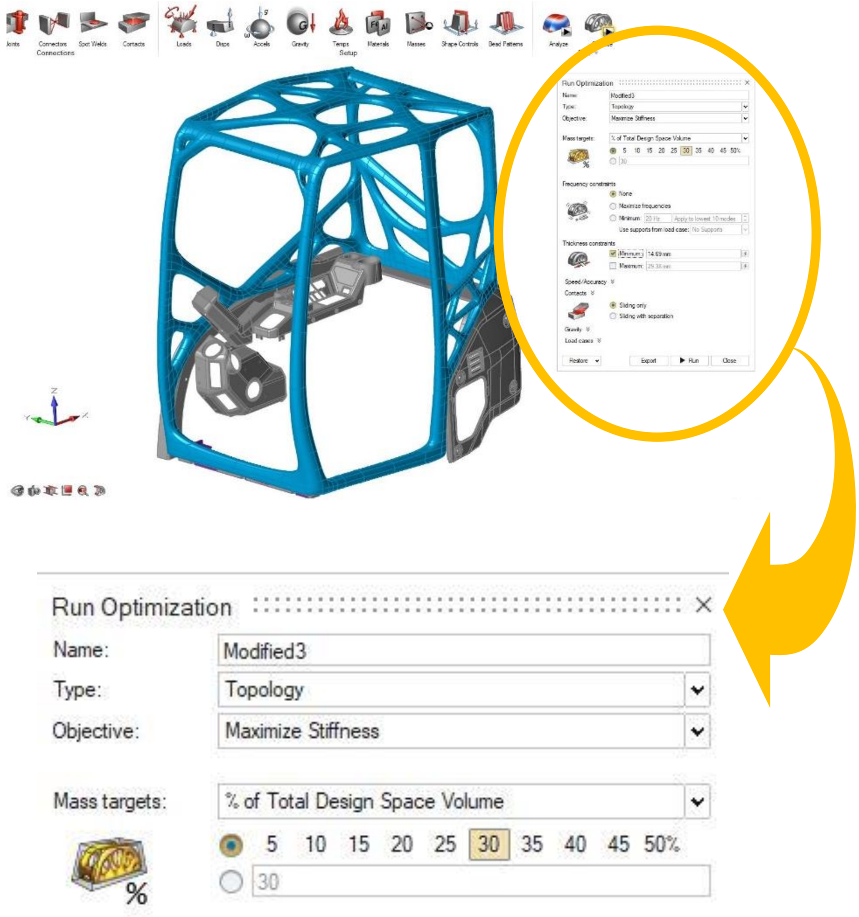



**Figure 3 Topology Optimization Tool of The SolidThinking Inspire 2018**

- **Case study 1: 3D printed Motorcycle Part Produced**

There was a project conducted in collaboration with ECOSSE Moto Works; a manufacturer of luxury motorcycles, ParaMatters; which specializes in topology optimization and lightweight design, and Reinshaw; a metal additive manufacturing system. The goal of the project was to make the upper mounting bracket lighter. The existing mounting bracket is made of aluminum and weighs 823g. Six static and vibration load scenarios were applied to design space and optimization was successfully achieved. The minimum safety factor was set at 3.0 and the frequency was set larger than 91Hz considering the mass of both wings. As a result, the 3D printed bracket was 35% lighter and had a load of 530 g [12].

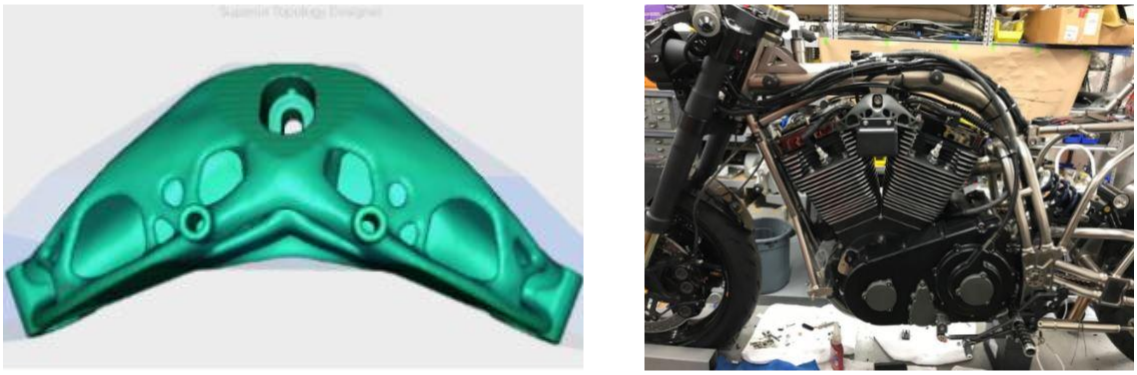


**Figure 4 3D printed upper bracket of the motorcycle using topology optimization**

- **Case study 2: Roof bracket of BMW i8 roadster**

BMW needed a complicated structure because it needed to push and pull a new bracket designed to lift the roof of the car. However, casting was impossible using conventional manufacturing processes. Maximilian Meixelsperger, the head of metal additive manufacturing, created a new type of roof bracket using 3D printing technology. The bracket was made lighter by way of topology optimization to satisfy the required load conditions. This roof bracket is 44% lighter than the original part and is successfully produced in 3D-printed part mass production despite its low volume [13].

**Figure 5    3D printed roof bracket of BMW i8**

- **Case study 3: The 3D-printed titanium concept wheels of HRE and GE**

HRE and GE additive created the 3D-printed concept wheel. This wheel was made titanium powder and a type of 3D printing called electron beam melting. It was divided into five components and those five pieces were combined with carbon-fiber wheel rim using titanium fasteners. To make high-quality engineering precision such as bolt holes and surface polishing, some machining processes was required. It is a case where the topology optimization in DfAM is implemented on a complex shape with a material difficult to process [14].

**Figure 6    New 3D-printed titanium concept wheel of HRE and GE**

## 2.3 Types of Additive Manufacturing process

As additive manufacturing continues to evolve, materials such as metals, polymers, ceramics, and sand can be used. The method of using additive manufacturing machines also utilizes various methods such as heat, laser, and UV light. As a result, various types of machines for additive manufacturing have been created and categorized machines having common points. There is an additive manufacturing process classified into 7 categories and definitions in the specification of "Standard Terminology for Additive Manufacturing Technologies." by the ASTM International Committee F42 [4]. Figure 7 classifies types of manufacturing according to materials and ASTM standards and shows typical AM for each item.

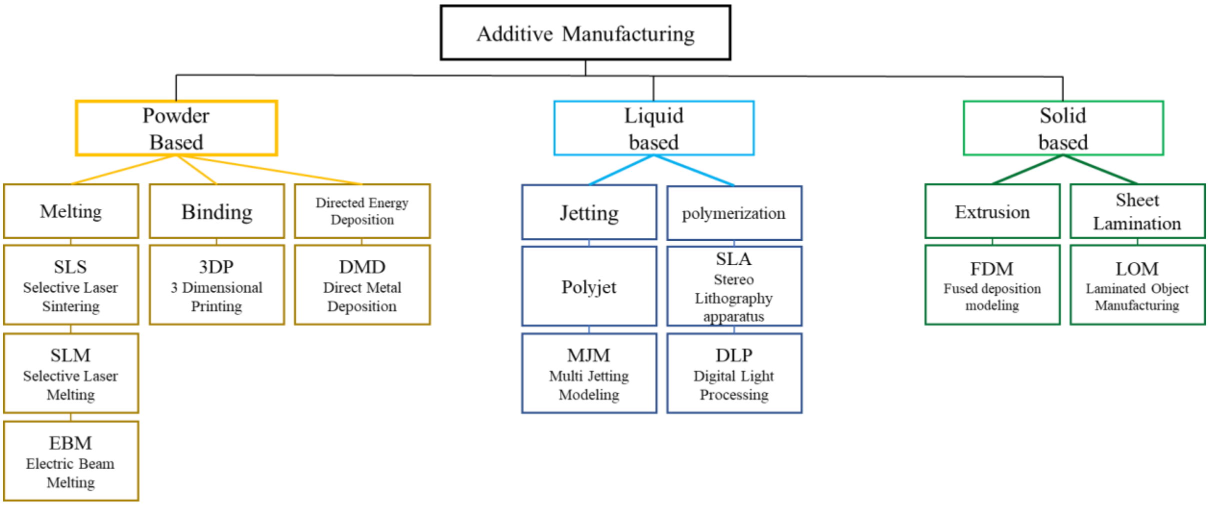



**Figure 7 Several types of Additive manufacturing**

In this paper, include the process of making an excavator cabin using LOAM. This section therefore only describes the additive manufacturing process involved in project creation. The first is the FDM scheme, which is comparative to LOAM. Second, SLS is discussed because it compares the advantages of SLS and LOAM in building large structures for the project. The third part explains polyjet because it makes several sub parts using the polyjet method in post-processing.

- **Fused Deposition Modeling**

Fused Deposition Modeling is a solid material base. Generally, a thermoplastic filament made in the form of a roll is used as a material. This manufacturing process has a print head for heating the material and supplies a filament to this head. The heated material is extruded into the nozzle, usually 0.25mm thick. The main materials used are polycarbonate (PC), acrylonitrile butadiene styrene (ABS), polyphenylsulfone (PPSF), PC-ABS blends, and PC-ISO. The FDM process main advantages are no chemical post-processing, no resins to cure, less expensive machine set-up and materials. The disadvantage is that the surface quality is low because the layers are stacked in the z direction. If the layer height is lower to smooth such a rough surface, the process can take several days. Therefore, the general FDM software gives the user two options. The software suggests ways to increase mechanical properties and surface smoothness by adjusting the density, and to create a minimal density and surface smoothness part. It is also to complete it in the shortest time [15].

- **Selective Laser Sintering**

Selective Laser Sintering is a powder material-based method. The material powder is sintered by a laser beam so that the laser fuses the powder along the path specified by the design. When one layer is completed, the bed is lowered by a certain height, and above it, a device called a recorder forms a thin layer of material. The powder used in this process may be a plastic, a metal, a metal polymer, a metal ceramic, etc. The polymer powders used are acrylic styrene and polyamide (nylon) and have almost the same mechanical properties. The main advantages of this process are the ability to select a wide range of materials, and unused materials can be recycled. The disadvantage is that the inert gas must be used to avoid oxidation and the accuracy is limited by the particle size of the material [9, 15].

- **Polyjet**

The Polyjet process is the process of manufacturing 3D models directly using inkjet technology. The inkjet head moves in the x- and y-directions, injects the material, cures the layer with an ultraviolet lamp, and moves the bed vertically in the z-direction to make the next layer. Usually, the layer height of this process is 16μm and the surface smoothness of the product quality is very high. However, the products produced by this process are less durable and easy to break. Support is made of gel material and is removed by spraying water at high pressure after the process is completed. The biggest advantage of Polyjet is that it can express various colors [15].

# 3. Large Object Additive Manufacturing

Fused deposition modeling ejects thermoplastic filaments into heated nozzles to create parts along 3D CAD data paths. Large object additive manufacturing is also similar to FDM in that it melts the material at high temperatures to produce parts. Large object additive manufacturing, however, supplies pellet materials to the extruder instead of thermoplastic filament material, which is heated and ejected into the nozzle by a screw located inside. For this reason, large object additive manufacturing is similar to injection molding processing [16]. In this chapter, the characteristics of LOAM are explained in more detail based on the researches of Oak Ridge National Laboratory, which led the development of BAAM (same meaning as LOAM).

## 3.1 Big Area Additive Manufacturing (BAAM)

An attempt to create a large-sized product began with the partnership of Oak Ridge National Laboratory (ORNL) and Cincinnati Incorporated (CI) in 2014. CI is a U.S. machine tool manufacturer. They have a 116-year history as a manufacturer and are a producer of sheet metal forming, shears and laser cutting systems. Their laser cutting technology can carry over 100 pounds of material, and their gantry system with linear electric motors allows precise movement at high speeds. CI’s linear electric gantry system is a suitable system for controlling heavy extrude in Big Area Additive Manufacturing (BAAM). Finally, ORNL and CI collaborated to develop BAAM equipment specialized in the production of large sized products, and CI successfully sold the developed commercial BAAM system to Sabic Inc [17].

## 3.2 Characteristics of LOAM

- **Possibility of Making Large-sized Products**

A typical method using polymer materials in the AM market is Fused Deposition Modeling (FDM). However, typical FDM processes have fundamental limitations; speed, cost and scale. FDM is a method in which a thermoplastic material is fed into a small heated nozzle and the material is deposited. Usually FDM limits the material flow-rate to 20 $cm^3$ / h for high part quality and surface finish. Thermoplastics, the material of FDM, has a high coefficient of thermal expansion (CTE). For this reason, the FDM process proceeds in an 'oven' to minimize thermal deformation. However, as the size of the part increases, it is difficult to control the temperature accurately, ultimately resulting in FDM having limited build volume. LOAM can be applied to the gantry system without oven constraints and it is possible to build a system without size restriction [18].

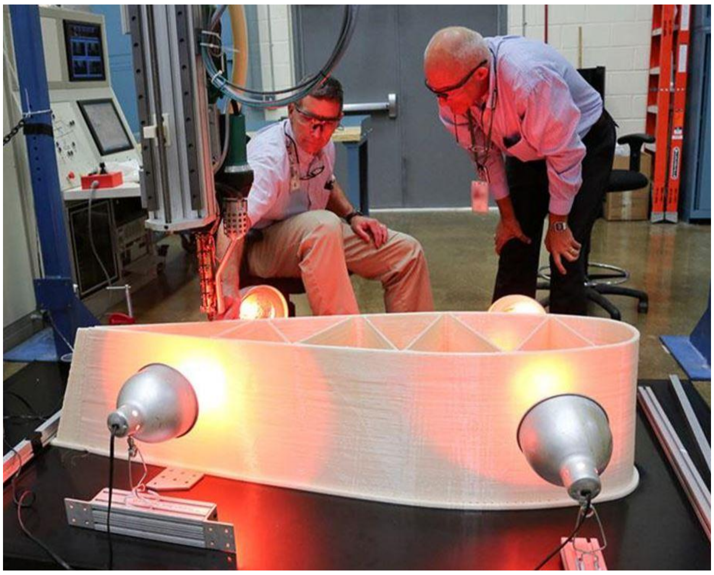


**Figure 8 Making large sized product using LOAM [18]**

- **Faster Build Rate**

Another major problem with AM is the slow build rate. LOAM has a build rate suitable for building large structures. LOAM has a build rate of about 5,000 cm 3 / h in an extruder with a diameter about 7.5 mm. ORNL created a large-sized product (1.2 m x 1.2 m x 1.5) that weighs 200 kg over 40 hours [18].

- **Combining Manufacturing Processes**

LOAM is able to produce large-size products quickly, but resolution and surface finish are not good. Therefore, an additional machining process is required to obtain a smooth surface. In order to solve this problem, a ball-mill router is added in the LOAM system to make a smooth surface shape [18].

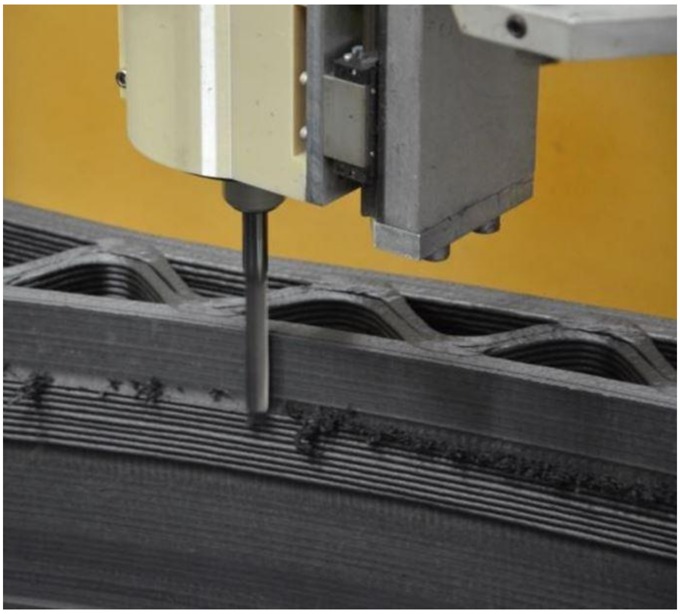


**Figure 9 The Ball-mill router in LOAM system [18]**

- **Inexpensive Material**

FDM considers two things to control feedstock material. The first is to supply the filament with a diameter of 1.75 mm, and the second is at the linear feed rate. Therefore, the process of making feedstock materials of FDM is difficult. As a result, the cost of FDM's ABS material is $220 /kg.

On the other hand, LOAM uses pelletized plastic found in injection molding, and extrusion industries. Therefore, the price of ABS pellets used by LOAM is about $1 /kg. And price of commercial carbon fiber filled ABS is about $5 /kg. Because of this, LOAM can be cost effective (~ 100X) by using commonly available material as feedstock material [18].

## 3.3 Carbon Fiber filled material

Carbon fiber-filled material means that the base material is filled with small fibers to improve their own mechanical properties. LOAM can use pelletized carbon fiber filled ABS as feedstock material. There are two major reasons for using carbon fiber filled ABS in LOAM equipment.

First, improved mechanical properties can be obtained. Fiber length is a factor affecting mechanical properties. The average fiber length is decreased which increases the fiber content of the composite. Fiber breakage occurs due to the interaction between the fiber and the surface of the device, the resin, and other fibers during compounding/mixing the resin with the fiber. As the fiber content increases, the interactions increase between the fibers, resulting in increased fiber breakage and shorter fibers. Fiber breakage occurs under high-shear mixing conditions [19]. ABS increase the strength and stiffness depending on the carbon fiber filled in the base material.

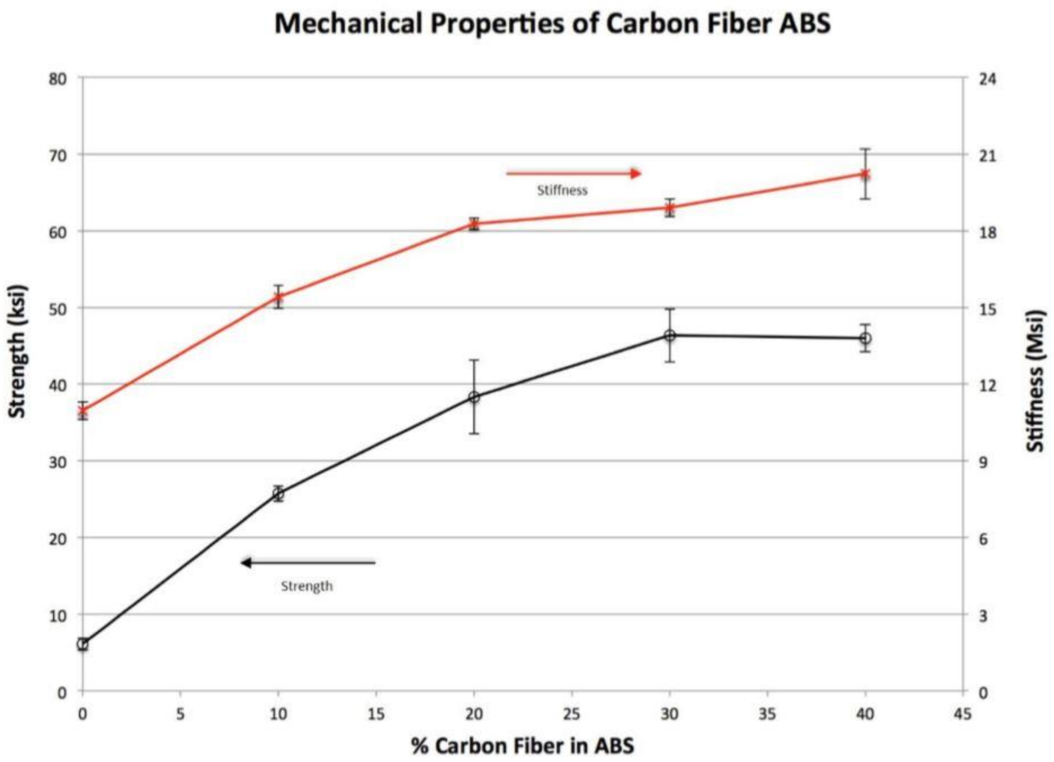



**Figure 10 Strength and Stiffness of carbon filled ABS**

In general, LOAM equipment materials can increase fiber loading up to 40% through short fiber-reinforced materials (<3 mm) [16]. ORNL tested the stiffness and strength of fiber-reinforced materials made with LOAM. The specimens were classified as 0-0 and 90-90 depending on the printing direction, and the material was made of ABS and 13%. CF-ABS strength, which has a 0-0 printing direction of 13% CF-ABS, was better than that of ABS as a printed specimen with a 0-0 printing direction. However, the specimens of 90-90 showed better physical properties than ABS and showed lower physical properties than specified. (Figure 11) [18]. This is because the fiber-reinforced material is extruded and deposited on the previous layer, which has increasing voids between the beads and reduces the contact area between adjacent layers. In addition, the mechanical properties of CF-ABS are strong, but they are weaker in certain directions than ABS unfilled because of their high anisotropy [16]. In the case of stiffness, there was no difference in stiffness of specimens which have printing direction (0-0, 90-90) made of ABS unfilled. However, in the case of 13% CF-ABS, the 0-0 direction specimen had about 1.2 Msi (7.72 GPa) exceeding the specification value (Figure 12). This increasing stiffness is due to the alignment of carbon fibers during the printing process [18].

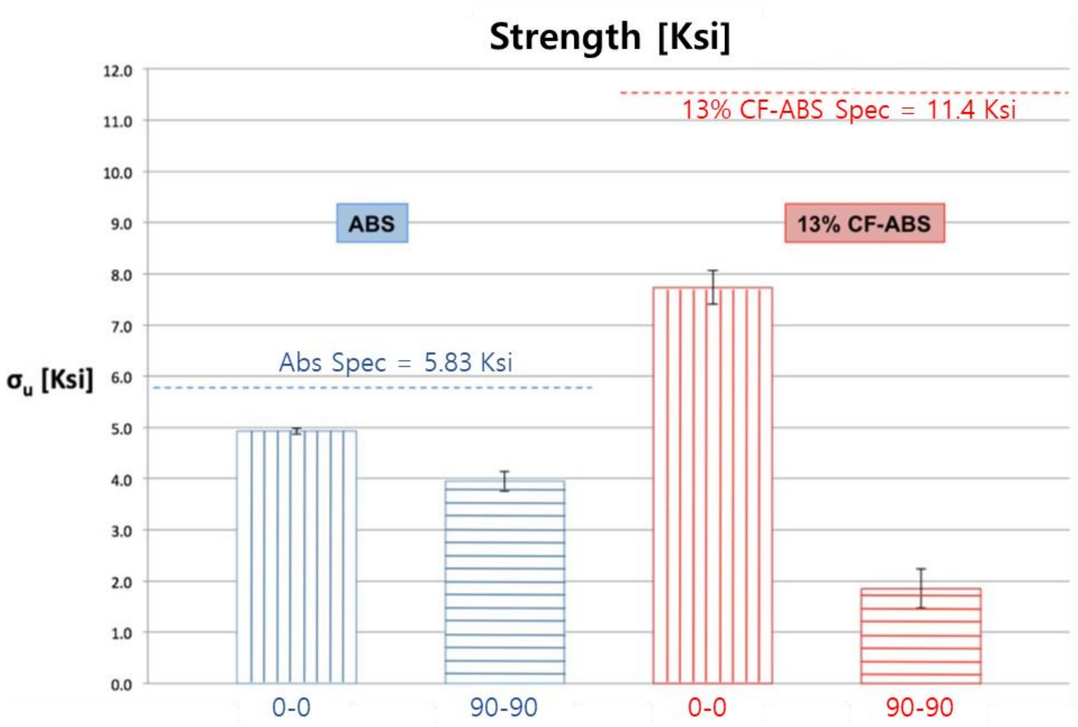



**Figure 11 Strength of ABS and 13% CF-ABS using LOAM**

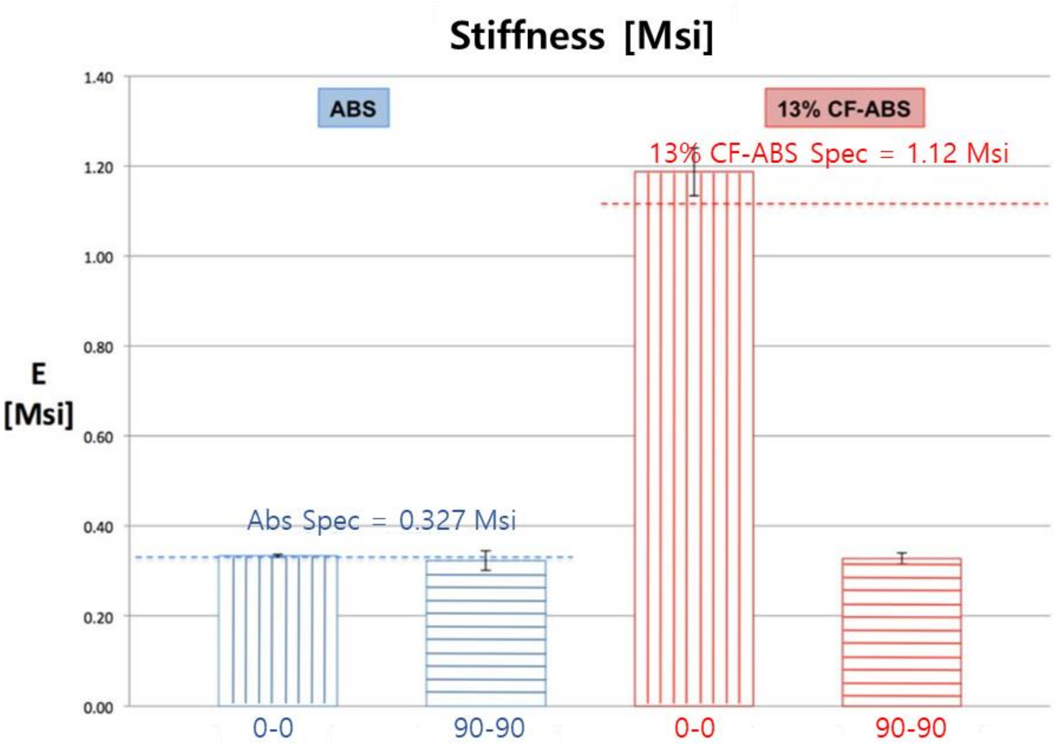



**Figure 12 Stiffness of ABS and 13% CF-ABS using LOAM**

Second, the coefficient of thermal expansion (CTE) can be drastically reduced. Thermoplastic has high CTE and results in thermal distortion occurring. However, using carbon fiber-filled material helps to minimize this phenomenon.   shows the CTE and thermal conductivity of ABS and CF-ABS.

**Table 1 CTE and thermal Conductivity for ABS**

| | CTE (μm/m°C) | Conductivity (W/m K) |
|---|---|---|
| ABS | 87.32 ± 6.17 | 0.177 |
| ABS/CF 13% parallel to deposition | 9.85 ± 0.84 | 0.397 |
| ABS/CF 13% perpendicular to deposition | 106.3 | 0.156 |

In the table above, the CTE and Conductivity values are very close to the ABS unfilled values. However, ABS-CF materials with parallel orientation have very small CTE and high conductivity values [19]. This means that carbon fiber-filled ABS have two advantages. Increased conductivity reduces thermal gradients and high stiffness with a reduced CTE value can limit part strain. In conclusion, using carbon fiber-filled material solves the residual stresses of products causing curl and warp through thermal gradients reduction and minimizes thermal distortion through reduced CTE and high stiffness.

ORNL created large parts using actual LOAM and compared ABS with / without carbon. The material was made of ABS and 13% CF-ABS (5 to 7 microns in diameter, 50 to 100 microns long), respectively. The specimens were made in sizes of 50 mm x 100 mm x 1.8 m. The left side is a CF-ABS bar and the right side is a ABS unfilled bar. The CF-ABS bar did not distort, but the ABS bar had a distortion of 45 mm [18].

**Figure 13 Distortion of ABS with/without carbon**

## 3.4 Considerations of the large object additive manufacturing

Large object additive manufacturing will be a specialized solution to produce for large structures. It can cover a much larger size than a typical additive manufacturing process and is characterized by very fast molding speed and low material cost. However, large object additive manufacturing still has some limitations in producing final- products. The designer should be fully aware of these limitations and minimize errors that may occur in the production of certain products. The following is a description of the limitations to consider for product manufacturing using large object additive manufacturing.

Alex Roschli et al., analyzes the problems that occur in the LOAM process in various aspects and suggests considerations. In this section, look at some of the major physical design considerations of the LOAM process based on the author's paper.

- **Bridging**

Bridging is a 3D printing structure that is created to connect parts located in different places. Bridging means the top layer is generated without support material on the hollow part. The process of stacking the top layer without support is printed in an empty space. As a result, should consider sagging while the top layer is stacked on top of two parts located. When bridging is printed, sagging is most affected by printers, materials and the environment. In the case of small printers, the surface area to volume is wide and the cooling fan is installed in the nozzle, so the material solidifies immediately after extrusion. In the case of LOAM, however, the surface area to volume is small and there is no cooling system. Because of this, LOAM requires a longer cooling time for the material to become solid. The material is also advantageous in producing bridging for materials with higher cooling efficiency, and at higher ambient temperatures, the beads of each plastic remain at higher temperatures, resulting in more sagging and failure to produce bridging. Figure 15 shows the results of several lengths of bridging with FDM printers and LOAM equipment. The authors have summarized the maximum distance of bridging as 1.85 “for a 0.3” in diameter nozzle and 2.25 “for a 0.2” nozzle [20, 21].

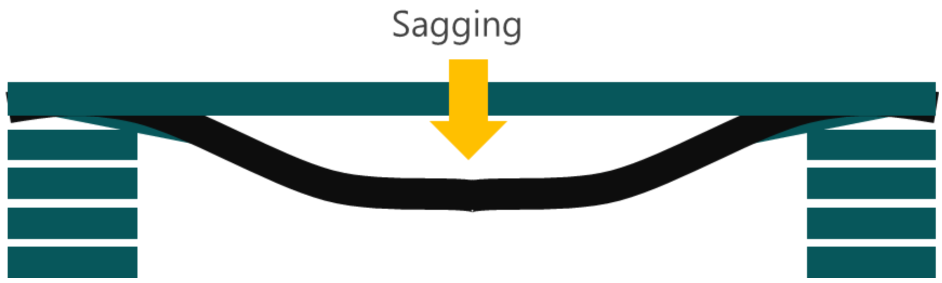



**Figure 14 Creating bridging without supports resulting in sagging**

**Figure 15 (Left) Bridging example printing using FDM, (Right) Test of maximum bridging distance of LOAM**

- **Strength of Z-direction**

Most AM processes carry material following in continuous contours in the x- and y-directions. And the z-direction is the direction of stacking the new layer over the completed previous layer. In other words, the z-direction is the direction in which the new material is melted and adhered to the solidified material. The adhesion between the solidified layer and the molten layer is much weaker than the adhesion between the molten beads in the same layer. As a result, the product has the highest strength in the x- and y-directions, but the strength in the z-direction is relatively low. Adding fiber reinforcement, such as carbon fiber, is a way to increase mechanical properties. However, the x- and y-directions increase the mechanical properties but do not increase the adhesion between the layers in the z-direction. For this reason, it is advisable to correct if the excessive load is concentrated in the z-axis direction at the product design stage [20].

- **Delamination**

Delamination is closely related to the material’s coefficient of thermal expansion. Delamination causes the underlying layer to shrink while cooling, and the upper layer undergoing printing is hot, part to curling. In other words, delamination is caused by shrinkage in the process of making a part, and temperature is the main cause. Delamination can lead to print failure, as well as damage to the printer head and part. In the case of LOAM, the delamination phenomenon is one of the main considerations because of the large part volume and the high layer height. To avoid delamination is to speed up the printing time and minimize the layer creation time. However, it is necessary to apply proper setting value to the printing speed. The authors of this paper provided a simple solution to avoid delamination. The problem is solved by adding another part in the same batch build. Even if each layer progresses at the same printing speed, the time for each layer to finish is increased and enough cooling time is provided. In addition, the additional batch of parts in the batch build increases overall process efficiency [20, 22]. Figure 16 is shown an example of failure of the excavator cabin part by delamination.

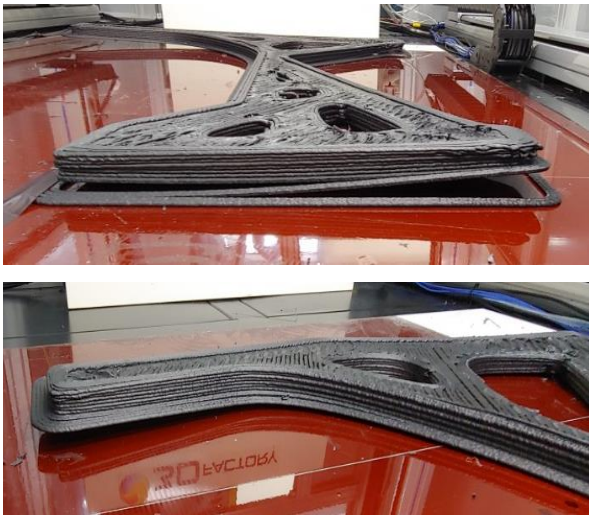


**Figure 16 A failure cabin part of Excavator due to delamination**

- **Without support material**

In the additive manufacturing process, supporter has the role of supporting structure on empty space. Overhanging structures, bridging with long distances, hollow shapes, etc. When print process is needed on an empty space, support is created and stacked on top of it. A supporter is required in the AM process to successfully produce complex shapes virtually. Generally, the support is removed after the process is eliminated. There are two ways to remove supporters. The first is to remove the support directly from the product and the second is to dissolve in the solvent tank. However, in the case of LOAM, it is difficult to directly remove the supporter from the part while the area of the support for supporting the large structure is widened and the adhesive force also increases simultaneously as increasing thickness of each beads. Dissolving is a harder solution. An additional tank larger than the part is needed to contain the solvent to remove the supporter. For this reason, in the case of LOAM, a shape should be created that does not create support in the design step [20].

- **Surface Finish and analysis of post processing for LOAM**

LOAM uses a larger nozzle than a small printer. The amount of material extruded at the larger nozzle produces higher layer heights and thicker beads. Therefore, the final part made by LOAM has a very rough surface. For small printers, post-processing is not difficult because the stack height is adjusted in millimeters. However, since LOAM has distinct layer boundaries and valleys, finishing of sophisticated post-processing is required to achieve surface smoothness to soften the rough surface of LOAM, and conventional manufacturing machines such as CNC are used [16]. Past et al., analyzed LOAM in terms of economy. The main analysis subjects are SLS, FDM, and LOAM, as well as the cost for preprocessing, material, processing, and post processing for each process and the percentage of each item in total process. In this paper, the cost of processing in SLS and FDM accounts for 89.8% and 58.7%, respectively. However, in case of LOAM, post-processing costs account for 45.5% of the total cost [23].

## 3.5 Experimental Setup

To make 3D-printed excavator cabin, 3D printing machine must have the ability to produce large sized objects. Company T is a domestic 3D printing machine developer and an additive manufacturing service provider. The LOAM system of company T is available to large sized part production. Their system can cover large sized part of about 1,200×1,600×1,100(mm). That machine parts build-up speed is 15~20 kg/h since extrusion heated nozzle has single screw. Also, it can use several composite materials such as ABS-CF, ABS-GF, PETG, etc. And, that machine uses pelletized feed stock. The materials are continuously fed through the pellet feeder. Figure 17 are the LOAM system of company T and the pellet feeder.

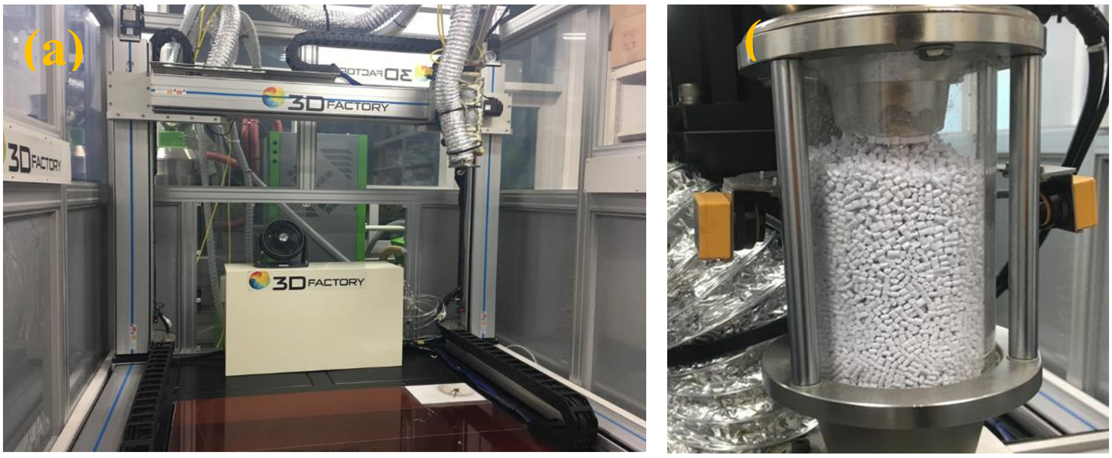



**Figure 17 (a) The LOAM system of company T, (b) pelletized material and pellet feeder**

In this paper has mentioned previously, Carbon fiber filled materials have many advantages in producing 3D printed parts and obtaining better mechanical properties. So, specimen test data about composite materials were required from company T. Figure 18 is shown several composite materials test data. These stress-strain curves show the results of the specimen test of 20% CF-ABS compared to those of other materials. In these data, 20% CF-ABS have the highest strength and stiffness. 10% CF-ABS and 20% CF-ABS have similar strength, but elasticity of 20% CF-ABS is higher than 10% CF-ABS. Figure 19 are SEM (Scanning Electron Microscope) images of 20% CF-ABS. These SEM images provided by company T show the composite fracture surface of the 20% CF-ABS. As shown, 6mm chopped carbon fiber in the ABS matrix is dispersed evenly with relatively directional orientation. For all these reasons, 3D printed excavator cabin made of 20% CF-ABS.

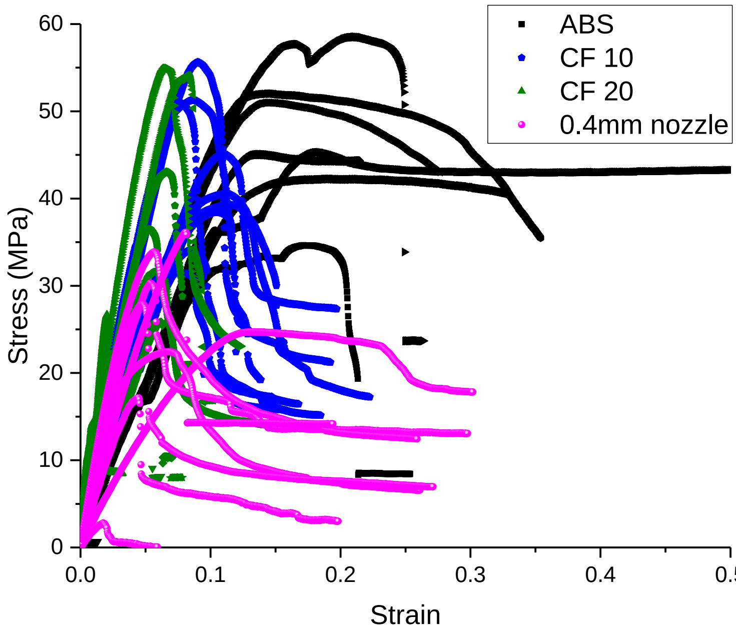



**Figure 18  Strain – Stress Curves of 3D printing materials**

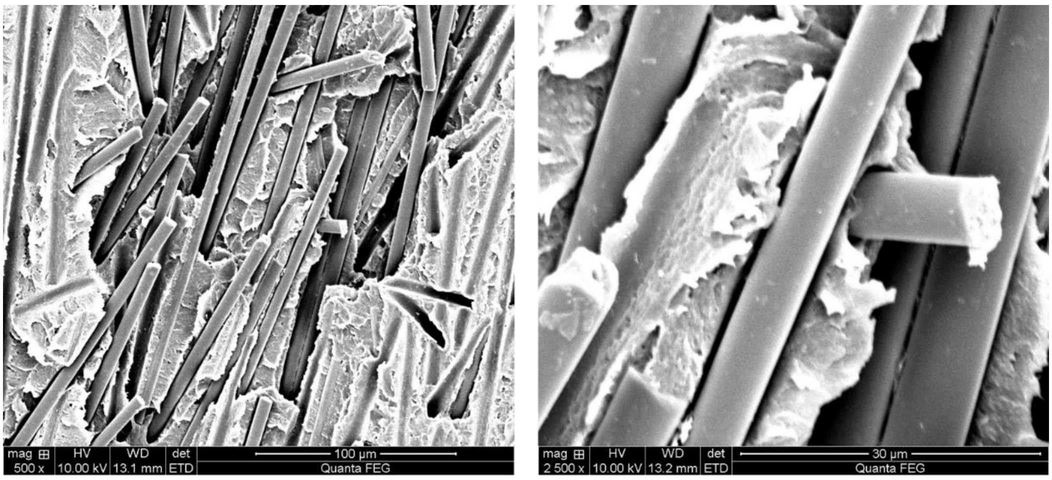



**Figure 19  SEM images of 20% CF- ABS**

# 4. Implementation and Application: Cabin design and manufacturing

## 4.1 Project Objective & Planning

There are actually a lot of things to consider before making a 3D-printed part. To implement the specifications of the product, the AM process must be applied to satisfy the requirements of the designer. AM machines have different batch sizes, build speeds and cost efficiency, and the mechanical properties and quality of products depend on the manufacturing method and material used. There is a simple example. Although a certain 3D printed product has a small volume, it must be mechanically functional, requiring perfect matching with other components. In this case, additive manufacturing that can realize high quality such as dimensional accuracy or clear surface finish of the final product is required. As another example, from the perspective of design, when making products with highly complexity designs such as porous structures or lattice structures, support should not be created, or post-processing should not be complicated. In conclusion, in order to maximize the use of 3D printers, it is necessary to identify the characteristics of the product and its purpose.

In this paper, there is a project to make 3D printing through the redesign of the cabin part of the 'H' company construction equipment. This project includes the process of fabricating large-sized products using the DfAM process. In addition, it is an example of using large object additive manufacturing for prototyping in real industries. This project will be one solution or a guideline that can effectively apply DfAM when developing a new 3D-printed part or using a new 3D printing machine. The following are the project objectives.

1. Creating large sized object parts from 3D-printed part through DfAM
2. Using ABS-CF composite material for 3D printing
3. Verification the availability of AM in actual industry

In the planning stage, begin with a precise understanding of the meaning of the project which are involved, and a precise understanding of the object that is to be created. Then select the equipment according to the characteristics of the object and set up the design and manufacturing plan.

The excavator cabin is an important part which protects workers in harsh environments such as construction sites and land development. In the case of using the original cabin, the internal shape and the external shape are formed by press working using a metal plate. Then, the inner steel plate and the outer steel plate thus produced are joined by spot welding. Because of this manufacturing method, current excavators have a variety of soft curved shapes despite their large structure. What had to be considered the most were the cabin dimensions. The cabin has a large volume of 1100 mm x 1400 mm x 1650 mm respectively. Figure 20 is a schematic showing the size of the cabin.

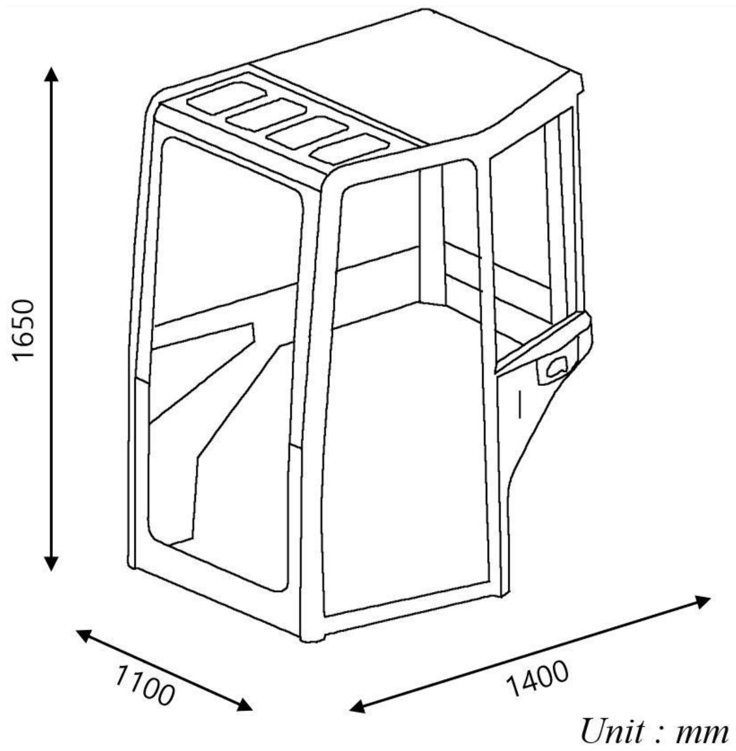
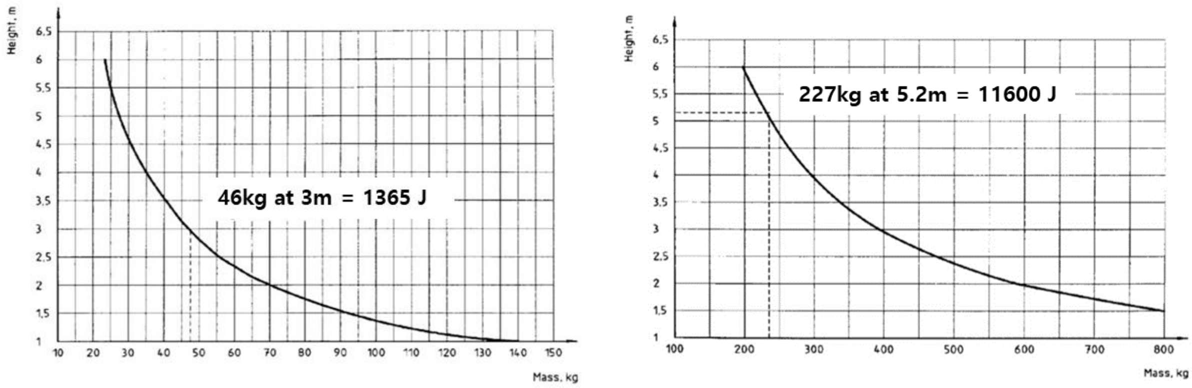



**Figure 20 The Excavator cabin with dimensions**

The environments in which the excavator is mainly operated are environments that are dangerous for people such as construction sites and land development sites. That is why the cabin must have the functionality to protect operators. The cabin should have sufficient stiffness and strength to protect people from external impacts. For operator protection, the ISO standard provides an object drop test method and minimum criteria for stability of the cabin structure. Company H conducts the test directly by referring to the above test method (Figure 21)[24]. Accordingly, Company H determines the stability of the excavator cabin through object drop testing in two steps to ensure the safety of the operator. Test Level 1 drops a 45 kg spherical object at a height of 3 meters. Test Level 2 drops a 300 kg spherical object from a height of 5 meters. (Figure 22).




A) Level 1 energy requirement curve

B) Level 2 energy requirement curve

**Figure 21  Hydraulic Excavators Falling object test criteria (ISO 10262)**

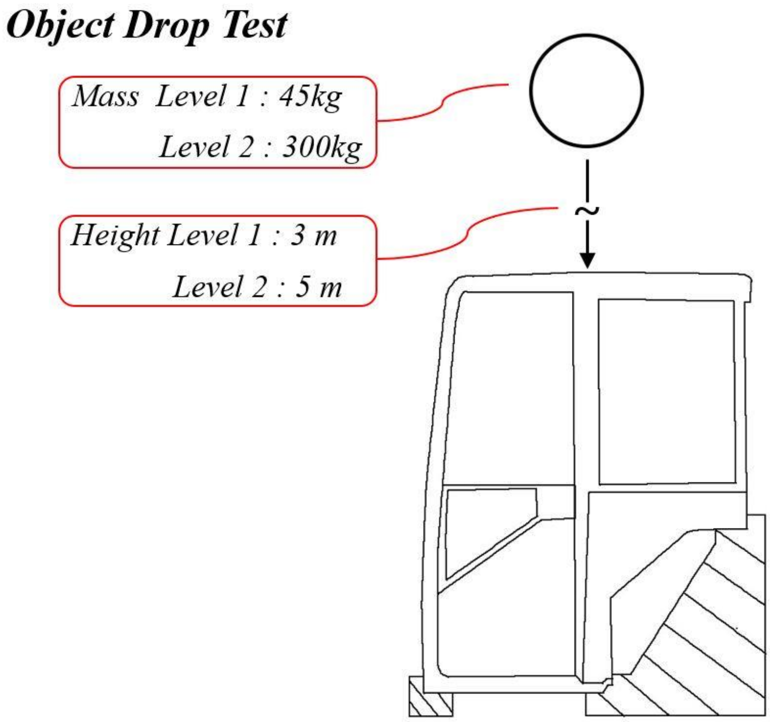



**Figure 22  Two case of object dropping test of excavator cabin in company H**

To summarize, consider the following considerations for additive manufacturing selection for making the cabin part of an excavator.

1. 3D printer capable of large- size objects
2. 3D printer available for composite materials
3. Does the 3D-printed part have good mechanical stability?

Based on these considerations, there are two options for AM selection. First, using Selective Laser Sintering (SLS). There are several reasons for selecting a SLS manufacturing process. The SLS process is infinite in design complexity because there is no supporter, and there are few design or equipment constraints. Therefore, designers can freely insert shapes such as topology-optimized results or lattice structures. That is, it can easily create the shape that has the maximum structural stiffness and a lightweight structure. Since the SLS process has a low layer height, the surface of the final product is very smooth, so post-processing is almost unnecessary. As a result of these, if simple sanding or blasting are required, it's possible to paint and use it as a finished product.

Another option is to use Large Object Additive Manufacturing. Large Object Additive Manufacturing can produce objects with a unit meter size. If the number of parts is increased, the design of the assembly part is added accordingly, and the time for assembly is increased. As a result, the entire production process is time-consuming. The fact that a large size object is produced means that the assembly process can be reduced. Table 2 compares the characteristics of SLS process and Large Size Additive Manufacturing. The criteria are set as follows (Table 2).

- Divide the number of parts required for SLS process and Large Object Additive Manufacturing by referring to actual size and design of the excavator cabin.

- The number of batches is calculated according to the actual production process.

- Estimated total printing time is the number of batches multiplied by the printing time per batch plus the cooling time.

**Table 2 Comparison Large Object Additive Manufacturing to Selective Laser Sintering**

| | Large Size Additive Manufacturing | Selective Laser Sintering |
|---|---|---|
| Maximum production size | 1,200 × 1,600 × 1,100 | 700 × 380 × 580 |
| Composite materials | Available | Available |
| Surface roughness | Very roughness | High quality smoothness |
| Design complexity | Low | High |
| Number of batches | 4 | 4.5 |
| Estimated printing time per batch | 6 hours | 28 hours |
| Cooling Time | 1 hour or less | 24 hour or more per batch |
| Estimated total printing time | 28 hours | 10 days |

It is necessary to provide a flexible option for large 3D printing prototyping and process improvement purposes with our H project. Because of the slow design process and the additional design process required for the assembly process, the SLS process is required to realize high design complexity and high product quality. However, post-processing would be required due to the surface roughness, Large Size Additive Manufacturing with the advantage of printing large objects quickly. There is no need to wait for the company's decision. This is another advantage of the AM process, which allows flexible deployment between manufacturing and design plans. As we proceed with the initial 3D printing part design, we can confirm the final design through flexible design modification and consultation reflecting Company H's final decision.

## 4.2 Design Process of Excavator Cabin

### 4.2.1 Initial Excavator Cabin design

The initial design process begins by setting the design space with reference to the overall dimensions of the most basic excavator cabin. The advantage of AM is that it can fabricate directly from 3D CAD data, so the initial design space work is very fast, referring only to the most basic dimension data. The parts of the bracket are set as fixed points and the design space is made as shown in Figure 23 by referring to the cabin's external shape. In order to provide the operator with a free working environment, the shell is specified with reference to the internal shape.

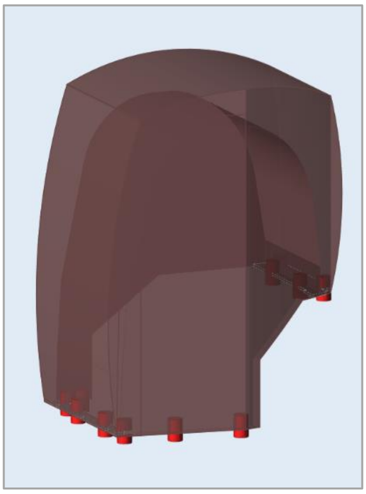


**Figure 23 Initial design space of Excavator cabin**

After setting the design area, we decided to make the design concept using the Topology Optimization method. The aim is to minimize compliance by considering only the direction of the load while focusing on the calculation of the density of the material for the purpose of lighter weight while maintaining the structural rigidity. Instead, we refer to the Topology Optimization results of several different load cases to derive the major shapes that the cabin should have and create a structure for load distribution. Figure 24 shows three Topology Optimization results with different load cases.

First, Figure 24 (a) is shown the topology optimization result with 1000 N load applied to the top. In this result, the material was placed in the shape of a four-point support structure at each corner of the Excavator Cabin. In conclusion, we decided to design a cabin with a four-point support structure by referring to this topology optimization result.

Figure 24 (b) shows the topology optimization result with a load of 1000 N on the front. It was confirmed that a truss structure for appropriately distributing the load of the front portion was generated in the upper plane and the left and right-side plane. Therefore, this truss structure is applied to the side and upper part.

Figure 24 (c) is shown the topology optimization result with 1000N at the top and front at the same time. (a) results and (b) results show that there is a need for relocation of materials. Initial design is made referring to topology optimization result that load is applied to top and front at the same time, and unnecessary layouts are identified, and parts that need reinforcement are found and reflected in design.

Figure 25 is shown initial design for excavator cabin with reference to results of topology optimization. In order to protect the operator as a whole, the frame is placed in a shape that wraps around the seat position and reinforced with a truss structure to withstand the load.

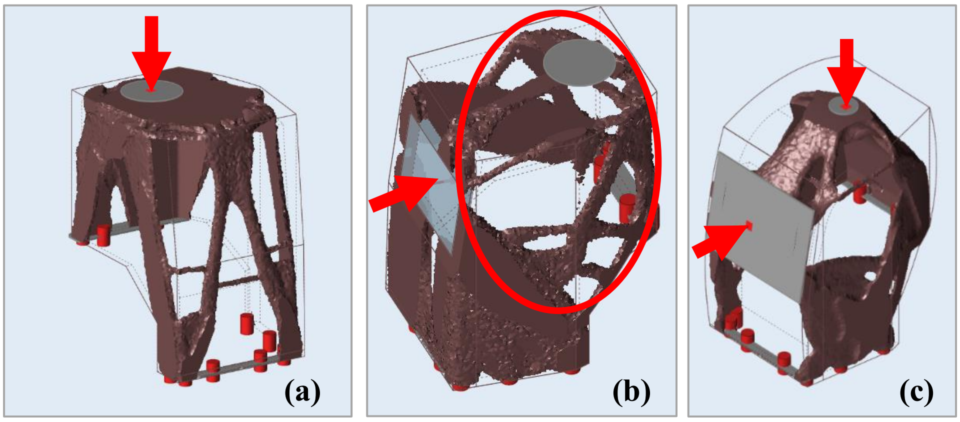



**Figure 24  Results of topology optimization with different load cases**

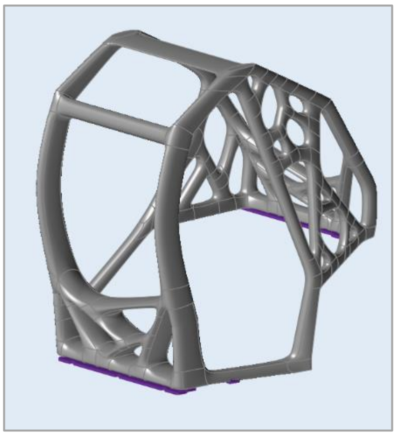


**Figure 25  Initial design for excavator cabin**

### 4.2.2 Modifying Excavator Cabin Design

After completing the initial design, modification work was done based on feedback from the Company H. Finally, the AM process selection was finalized, and the final design of the excavator cabin was completed according to the characteristics of the 3D printer to be used. Figure 26 is shown the flow chart of the modification process.

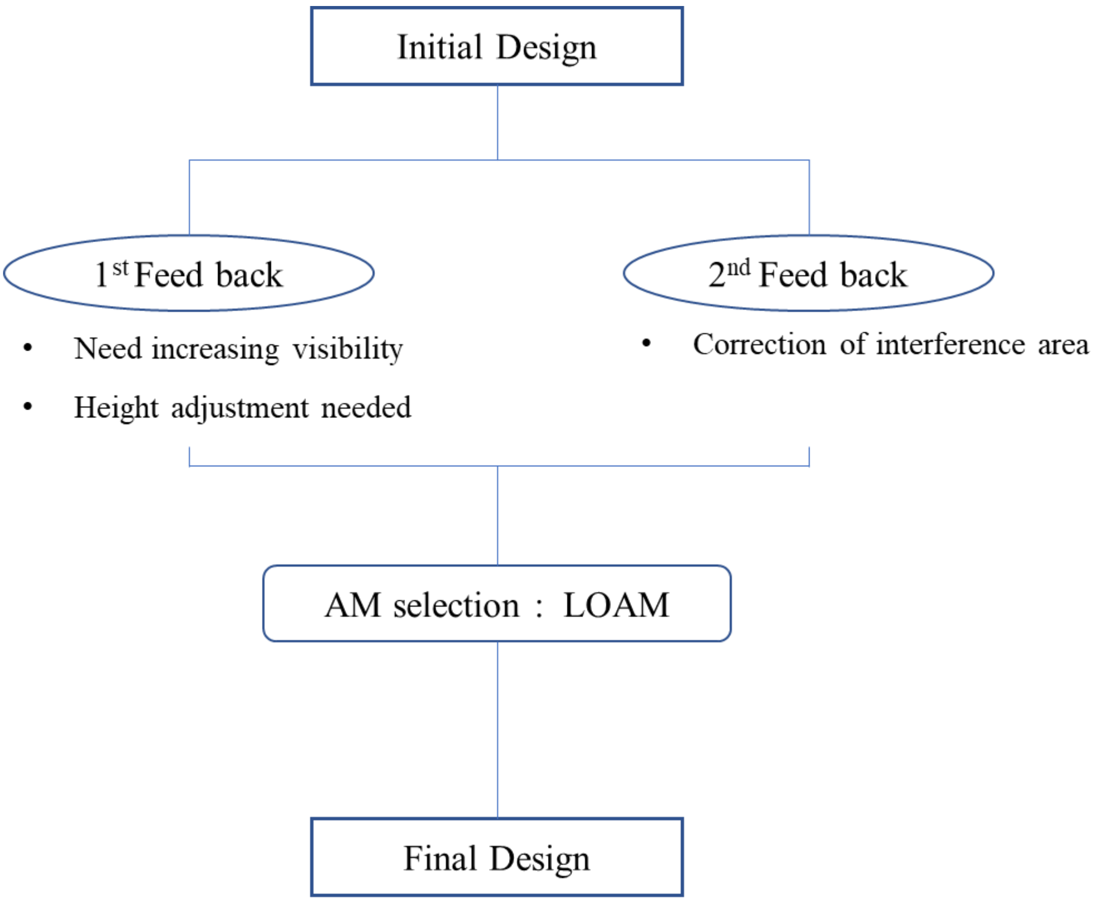



**Figure 26 Flow chart of modification process**

The first feedback given by Company H was the need to increase visibility. It was Company H's opinion that the operator was too much interfered with the cabin's structure. Company H also requested that the cabin's top height match the original CAD file as much as possible due to the safety restriction. Based on the feedback, the top plane was modified in accordance with the original CAD data of the cabin by height constraint and the obstructing structure was removed to improve the view of the operator.

The second feedback from Company H was a modification of the correction of the interference area. To mount the cabin, check whether it is interfering with other parts. Company H confirmed the possibility of assembly using the full 3D CAD data of the excavator. As a result, the interference area was found in the following part. Significant interference occurred in the left part of the cover, the right part of the console. Therefore, the interference area was modified based on the CAD data additionally provided by Company H (Figure 27).

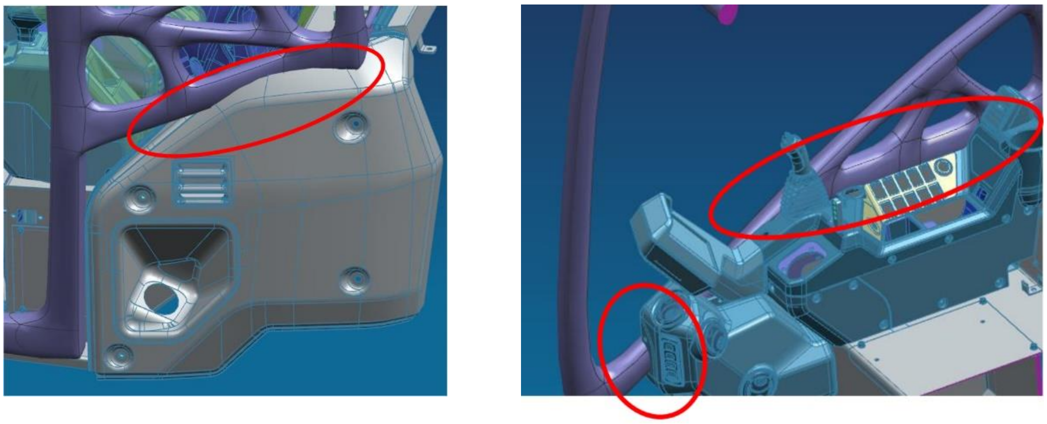


**Figure 27 The second Feedback to modify interfering area of side parts**

The AM selection process has been proposed to Company H with two options, SLS and LOAM, to provide the flexibility of choice (Table 2). We also decided to provide visualization of the two manufacturing processes based on the design reflecting the second feedback. Figure 28 compares the result design with the most issue printing time and number of parts. Company H's final decision of AM selection was to use Large Object Additive Manufacturing, which can output all parts in a much shorter time and with a significantly smaller number of parts. The purpose of the project is to quickly create 3D-printed large structures in an easy way. Figure 29 shows a cabin design which changes from initial design to final design to use LOAM.

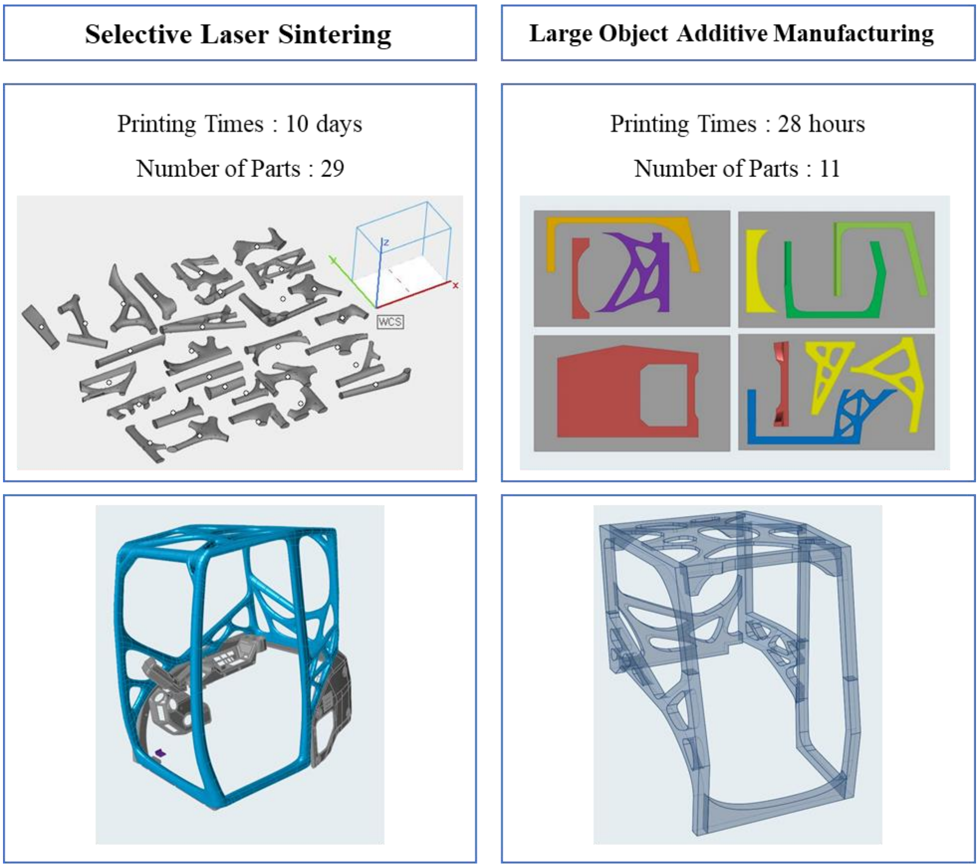



**Figure 28 Process capability of SLS and LOAM**

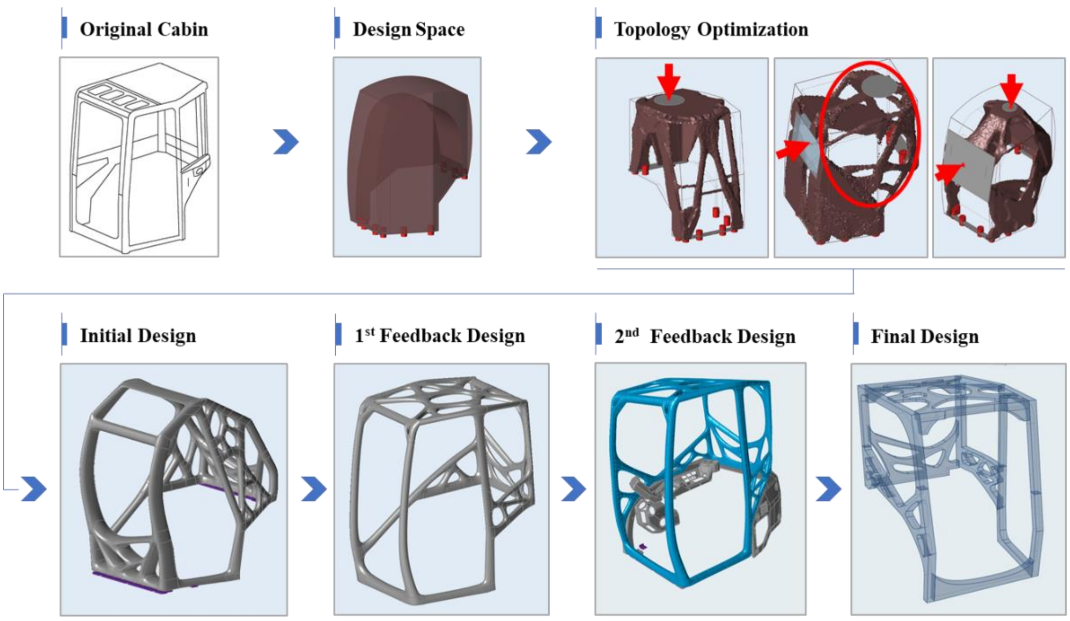



**Figure 29 Designing steps of Excavator Cabin**

### 4.2.3 The Finite Element Analysis of Excavator Cabin

A computational simulation process was needed to ensure that the two final designs had an enough strength and stiffness and satisfying safety before physical prototyping of the excavator cabin. In this project, only basic and simple simulations were performed as a safety verification procedure. There are two assumptions for the FEA. The first assumes that the part is one. In other words, it was not divided into several parts depending on the size of the 3D printing machine bed. The second assumes that the part is made isotropic. The SolidThinking Inspire 2018 provide not only topology optimization tool but also finite element analysis. Figure 30 is how to set FEA methods in Inspire 2018. Element size is set to 10mm. Table 3 is mechanical properties of 20% CF-ABS used in the analysis. The load case was applied a static load of 1 ton on the top part and the front part of the design simultaneously.

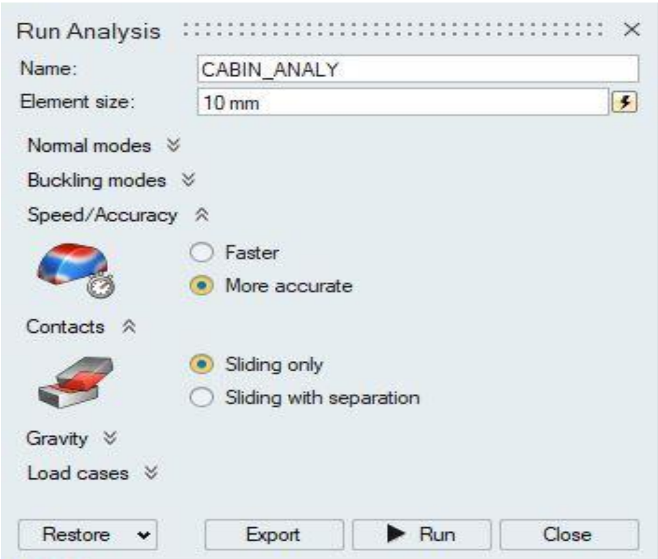



**Figure 30 The Finite Element Analysis tool settings for 3D printed Excavator Cabin in Inspire 2018**

| Mechanical Properties | 20% CF-ABS |
|---|---|
| Elasticity | 12.900E + 03 MPa |
| Poisson's ratio | 0.290 |
| Density | 1.140E – 06 kg / $mm^3$ |
| Yield Stress | 103 MPa |

**Table 3 20% CF – ABS Mechanical Properties used in the FE analysis**

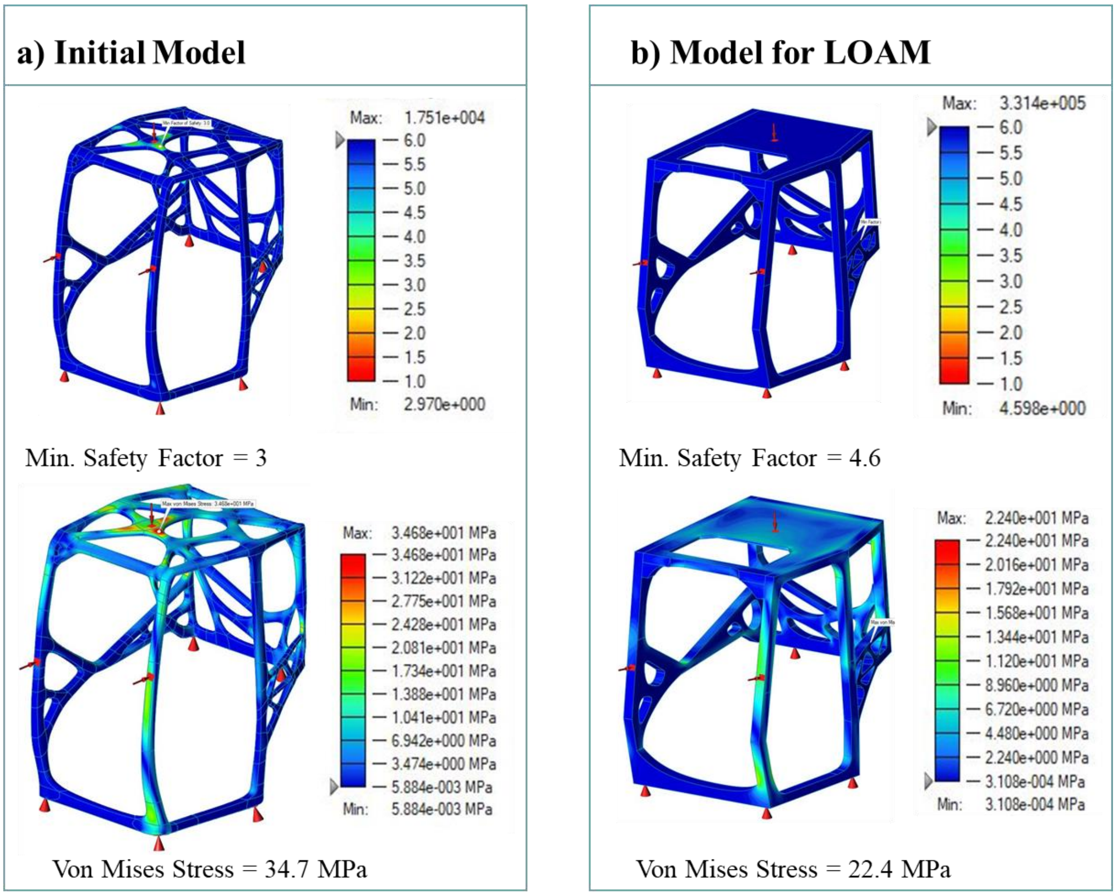



**Figure 31 FEA results of Excavator cabin. a) is an initial model design, b) is a modified design for LOAM**

Figure 32 are shown the results of FE analysis. The minimum safety factor of initial model is 3 and LOAM model is 4.6. And the results of von mises stress of initial model is 34.7 MPa and LOAM model is 22.4 MPa. According to these results, the initial model and final design can be considered to have safe structures through FE analysis.

## 4.3 Physical Prototyping

The company's final decision was to simplify the assembly process by facilitating large part production by applying the LOAM process. The equipment used for physical prototyping is large 3D printing developed by Company T. Therefore, all the data compared in this chapter are based on the equipment of Company T. This step is a summary of the issues that arise during the physical prototype printing process.

### 4.3.1 Adjustment Toolpath: High quality part production

After the design stage, CAD data designed to use LOAM is required to input the information and parameters of 3D printer equipments such as layer height and nozzle diameter, and to generate toolpath accordingly. Company T has succeeded in producing large-size products several times using its own developed programs and several open-source toolpath generator programs. Company T has an important preparation process for making large structures. When the toolpath is generated, the overlap between different located toolpaths can cause excessive laminating of the material. Therefore, it is necessary to modify the CAD model to minimize the overlap between the toolpaths of the final modeling considering the present situation. Figure 33 shows Case 1, which is the result of printing the toolpath of one part on the left side of the cabin while remaining overlap, and Case 2, which is the result of printing after minimizing overlap. In Case 1, overlap occurs every time the layer goes up, and the operator has to continue to remove it. If the operator was unable to perform removal of overflowing materials, the nozzle would have to collide with the projecting portion to temporarily stop the printing operation. In Case 2, after confirming where part overlapping occurred, the overall thickness of the part was adjusted by 1 to 2 mm to minimize the overlap. As a result, the unnecessary stacking of the material has been reduced and the final part has been created without any additional work by the operator.

Complex shapes were also created using LOAM. However, the internal small edge or triangle toolpaths caused by the curved, circular, or elliptical parts of the part are the main cause of imperfections of the part. Figure 35 shows that when the part where the edge or triangle toolpaths exist in the toolpath is actually printed using LOAM, the part surface cannot be reliably filled. For this reason, the outer contour is made of a 3-line wall, and the toolpath is adjusted to fill the interior with a diagonal pattern. As a result, imperfections of parts with complex toolpath have been reduced. Figure 34 shows whole printed parts placed in the workshop to assemble them.

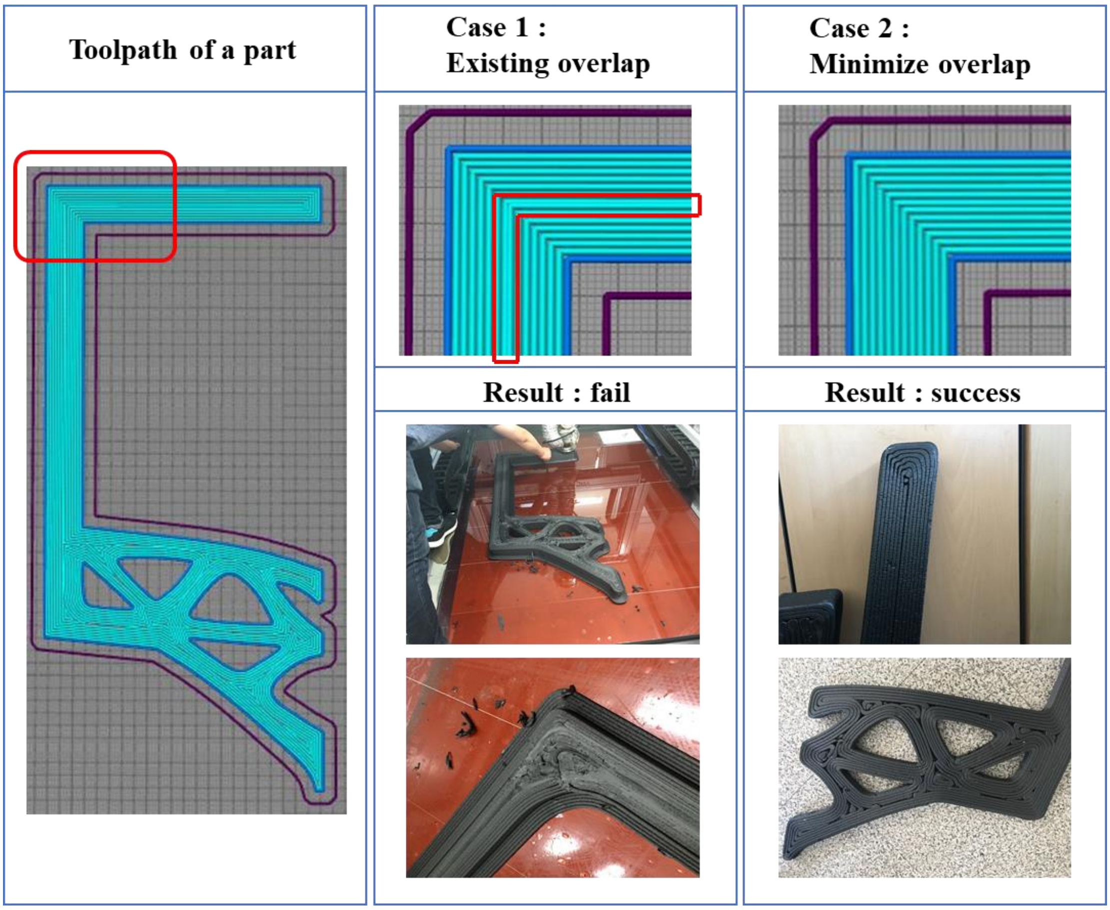



**Figure 33 Minimizing overlap of toolpath through adjustment thickness of the part**

**Figure 34 The Completion all parts of 3D printed excavator cabin**

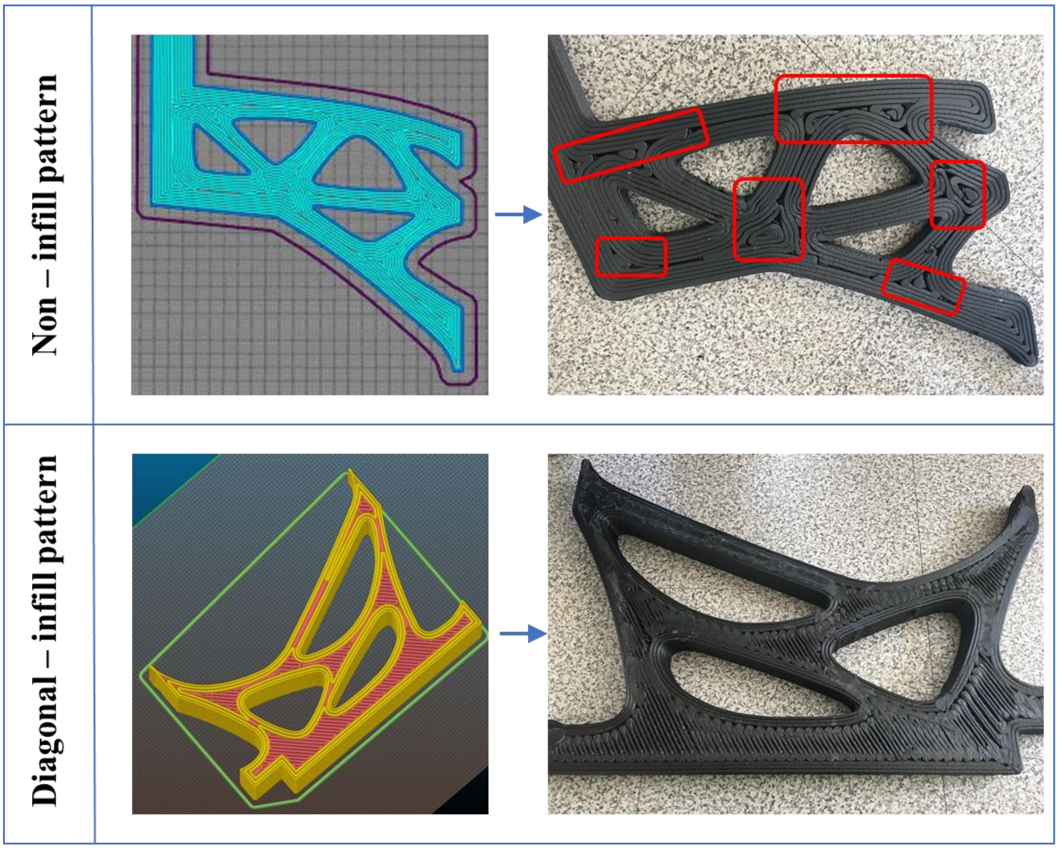



**Figure 35 Reducing imperfections of part through toolpath adjustment**

### 4.3.2 Assembly & Post Processing

In the assembly Stage, it was important to consider parts weight. Company H was satisfied with the quality of final parts. However, concern was expressed about the assembly process. Parts were generally large in size and weigh more than 10 kg. Company H requested an answer on how to assemble the parts made of polymer. The assembly plan established in this study is as follows.

1. **Avoid using additional Jig & Fixture**

   Jig & Fixture helps to prevent twisting and deformation that occurs during the assembly process by fixing the separated parts to the structure and keeping them in a state of assembling. However, additional designs and processes are added to create a Jig & Fixture. This study gives priority to part assembly and demonstrates the possibility of making 3D-printed large structure without additional Jig & Fixture using simple hardware

2. **Adoption Commercial Hardware**

   The 3D-printed parts of the cabin have a large volume and weight. For this reason, bolts and nuts are used to firmly assemble each part. Utilizing commercial hardware such as bolts, nuts, and steel brackets that can be purchased from anywhere, it shows that it is possible to assemble without the need for special tools and processes and increases accessibility

In the conventional manufacturing process, the inner and outer parts of the excavator cabin were made by a stamping process with sheet metal materials. Then, each part is assembled by spot welding. In this project, the main material of the 3D-printed excavator cabin is polymer. Therefore, it is not possible to assemble each part by welding and there is a need to approach in different ways. To assemble the 3D printed cabin parts, it was attempted to assemble each part using commercial hardware. However, each assembly site must withstand various constraints such as load and vibration of the product itself. The following explains how to combine large structures made of polymer materials.

■ **Method 1. Joining Parts Without Additional Hardware**

In this case, different 3D-printed parts are joined without additional parts. Normally, a hole machining process is used to fasten bolts and nuts. It is possible to make holes during the printing process; however, in case of LOAM, the quality of a hole has a very low resolution, and it is possible that it cannot fulfill its function. Since there are sufficient areas between the parts except for the part subject to hole machining, there is no problem in maintaining it as one object when assembled. If a part can include a bracket shape, it can be used in the design stage to directly connect each part. In Case 1, it is also possible to naturally hide the joints if the part itself has sufficient thickness (Figure 36).

**Figure 36 Method 1: Parts assembly without additional hardware**

■ **Method 2. Joining Parts with Steel Brackets**

In this case, one part is divided and assembled on the same plane, and bolts and a nuts cannot penetrate the parts, so they must be fixed using brackets. If a bracket is used on only one side, a bracket may be folded due to the load. Therefore, the part on the same plane should be positioned with the brackets on both sides and joined with bolts and nuts (Figure 37).

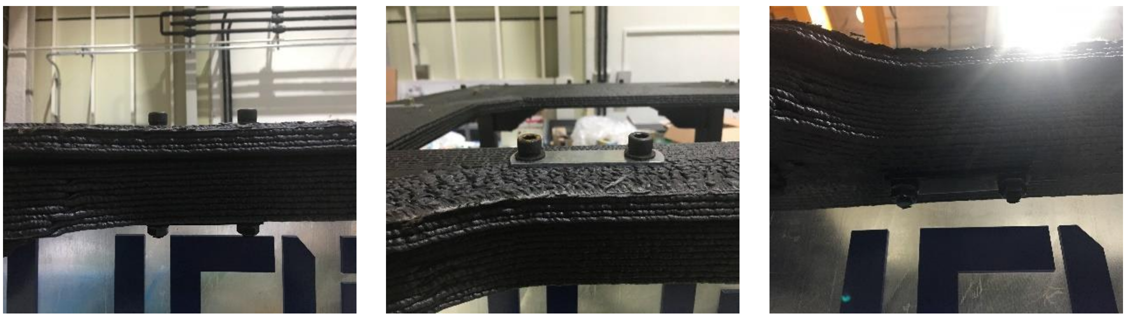


**Figure 37 Method 2: Parts assembly with steel brackets**

- **Method 3. Joining Parts with Bonding Material**

In this case, bonding material can be used to increase adhesiveness and completely fill the fine gap. Bonding material is spread out between divided parts. After machining the holes, fasteners are used to assemble divided parts. This method requires additional time for bonding material to be injected and dried, but it can completely fill the fine gap between each part. Therefore, it can be used as a useful method when waterproofing is required.

**Figure 38 Method 3: Fill fine gaps through bonding material for parts required**

- **Method 4. Add Joint Design to Each Assembled Part**

In this case, joint design is added to each part to improve assembly process convenience during the design stage. The design process can be complicated but slip phenomenon can be avoided because it can maintain the greatest bond between parts. Usually using groove and tongue joint or dovetail joint design will be effective. Figure 39 is an example of joining parts using dovetail joints and epoxy adhesives in ORNL [25].

**Figure 39 Method 4: Dovetail joint and epoxy adhesive to assemble divided parts in ORNL [25].**

The joining parts method can be considered as above. In this project, some of above methods were used in the assembly process. First, the parts divided in consideration of top/right/left parts are assembled (Method 2). Left/Right/Top parts, each group is divided into three parts. These divided parts are fixed with steel brackets and fasteners (Method 2). The left and right parts connected to the top part are joined relatively thicker fasteners (Method 1). In this case, the first hole machining is performed to the thread diameter of the bolt, and the second hole machining drills to the depth of the bolt head / nut size. Then, the left / right / top part were assembled and the front and rear supports were fixed with steel brackets to complete the cabin assembly (Figure 40, Figure 41).

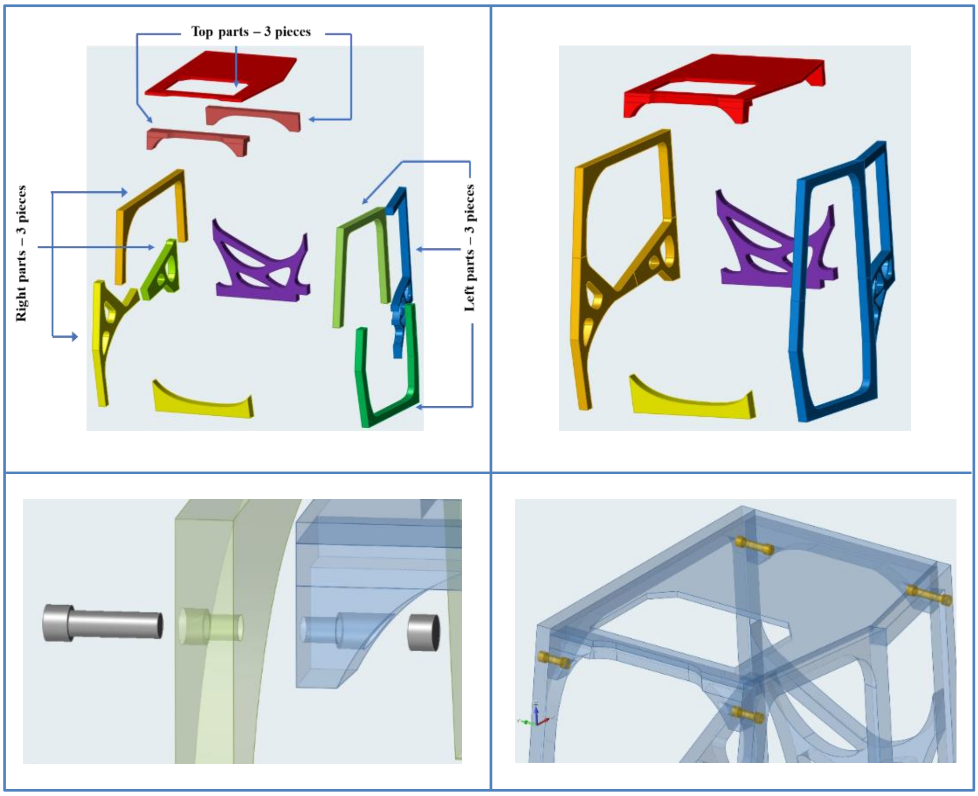



**Figure 40　Assembly Process Planning and Order**

Post-processing was simple with the cover of the bracket naturally showing the 3D printing structure. Covers were made to hide bracket protrusions. Covers were made using a polyjet printer with inserting the representative logo of each participating organization in the project. The cover was glued and the bracket where the cover was not placed was painted with black paint. Black silicon was used for adhesion and finish (Figure 42).

**Figure 41 Complete assembly of 3D printed excavator cabin**

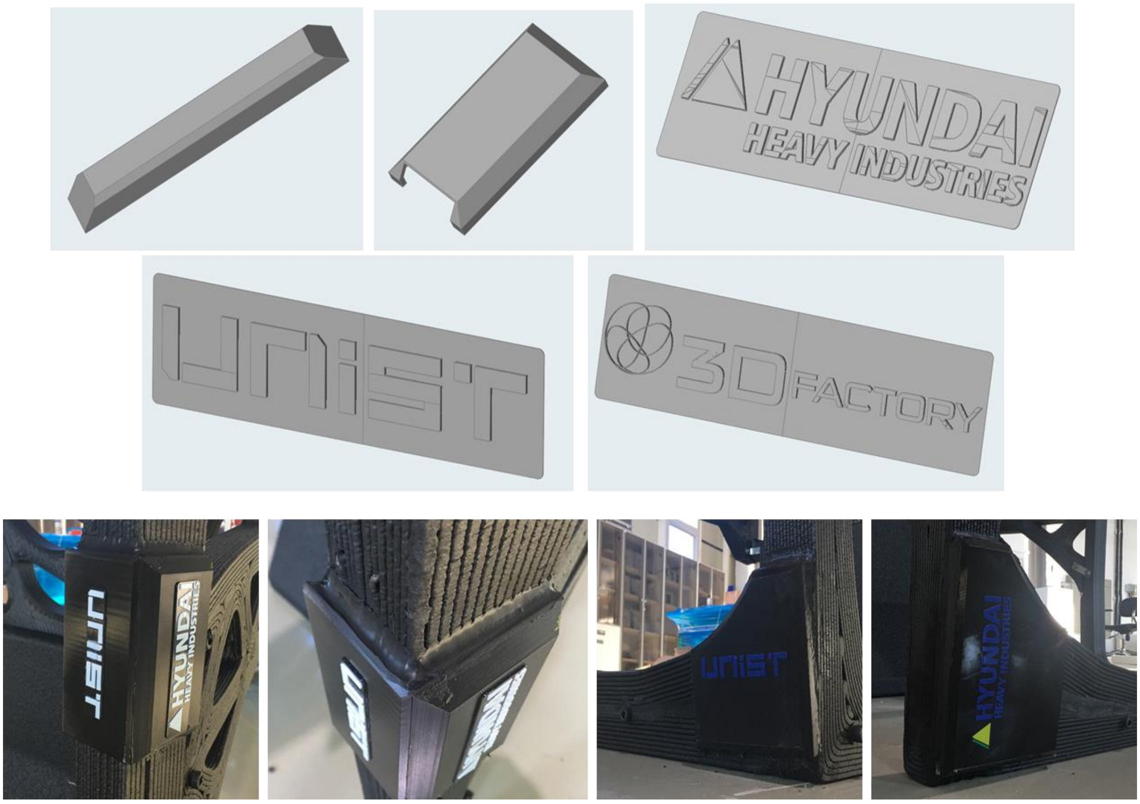



**Figure 42 Various cover models and actual application to cabin**

## 4.4 Demonstration & Validation

The final assembly of between excavator and cabin was carried out using the Company H's crane. The cabin of the excavator is composed of 11 parts in total and weighs 100 kg. The weight was measured using a crane. After the complete attachment of the excavator and the cabin, the cover parts made in the post-process were installed. The reason for later attaching the cover parts is to prevent breakage when final assembly proceeding.


**Figure 43 Final assembly process of between excavator and cabin, Project completion**

The ultimate goal of this project is to demonstrate how large products can be fabricated using 3D printers and their applicability in industry. Therefore, it is necessary to compare the AM process with the original process of the excavator cabin when proceeding with this project. The main process of excavator cabin is the stamping process to make the inner and outer shape, the machining process and the welding process to make it as one object. Here, the stamping process has been briefly investigated in terms of time and costs of mold development. There is no literature on the overall analysis of sheet metal forming costs in this paper. However, there are research papers on specific areas such as tooling costs, times, energy efficiency, and labor costs. In this paper, it takes more than 10 weeks to make a die set and a considerable amount of time is added depending on the types in the project. Moreover, in this paper, the cost of mold making, and necessary materials are summarized in the automotive parts and die set data provided by a Michigan die maker. To make a car hood, roof, front door outer, etc., a minimum of 5,000 kg to 23,000 kg of zinc material is required. The die-set cost is 40~ 60 million won. In addition, the correlation between the batch size and the cost for part production using stamping process is graphically shown. Since the 3D printing excavator cabin production cost is about $2,500 excluding the labor cost, it is more economical than the existing stamping process as long as the batch size is under 50 [26] (Figure 44). Figure 45 compares the important conventional manufacturing process and the additive manufacturing process. Through this project, The AM process can be connected to the assembly process via a simple machining process after direct parts fabrication. Therefore, there is no need for a stamping process to make the shape of the product, and the process of designing and manufacturing the Jig and Fixture is also optional. In conclusion, the stamping process is replaced with direct parts fabrication to create the most internal and external parts that make up the cabin, resulting in cost savings and reduced time required for development.

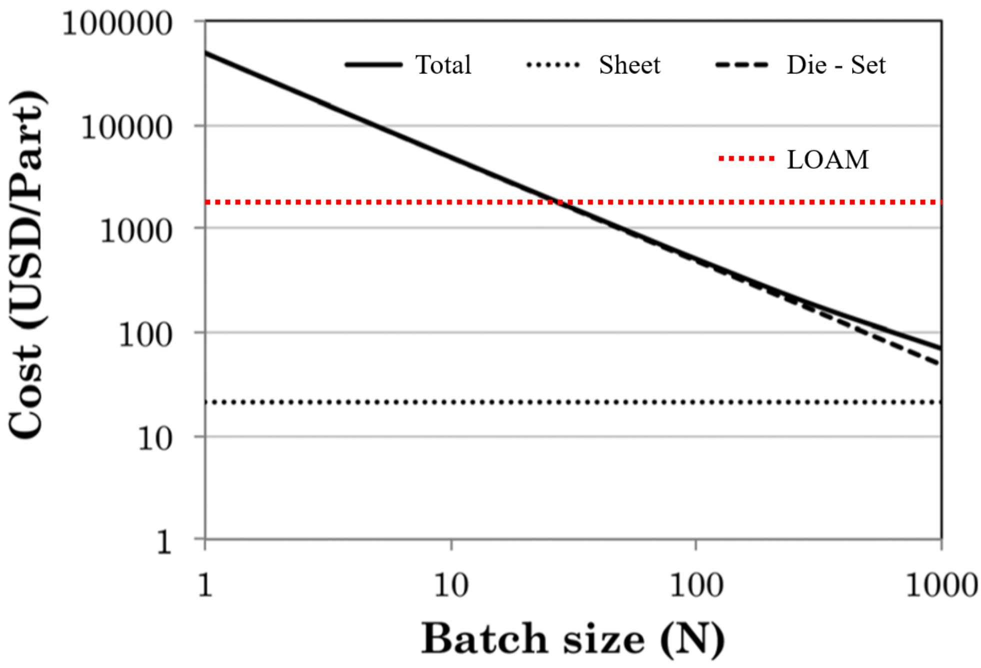



**Figure 44 The correlation between the batch size and the cost process using the stamping process and LOAM**

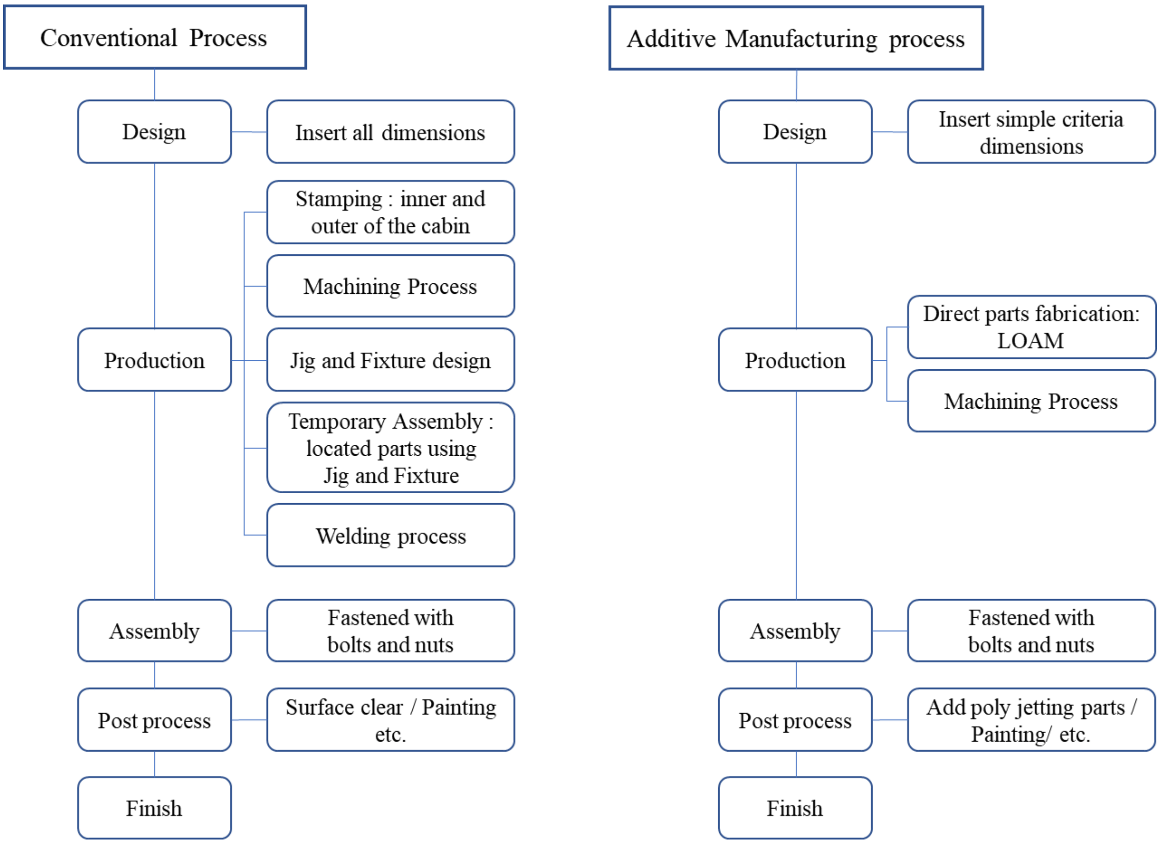



**Figure 45 Comparison process between Conventional process and Additive Manufacturing**

# 5. Conclusion

Over the past decade, the Additive Manufacturing field has seen significantly growth and new technology emerging. At present, additive manufacturing technology is not only affect in prototype manufacturing, but also successful examples of final product manufacturing are pouring out. It becomes possible to freedom from the constraints of conventional manufacturing process method and to realize the more advanced design as the feasibility becomes higher. However, there are still negative views that additive manufacturing is difficult to apply to industry. Obviously, the development of AM technology has made it possible to implement high-resolution surface smoothness, correct dimensional accuracy, and high mechanical properties as final products. However, over the decades, AM has not been aware of the ultimate problems in real industry as AM develops within its own constraints. The fact that AM process is not a big advantage for the size and production of various products made in real industry.

However, new methods of additive manufacturing are attracting attention in order to offer solutions from the point of view of real industry. Large Object Additive Manufacturing not only allows the size of large structures to be created, but also has the advantage that build-up speed is much higher than other Additive manufacturing processes. Therefore, in this study, Excavator cabin applying Design for Additive Manufacturing (DfAM) which make full use of advantages of AM capabilities was made using LOAM. The ultimate goal of this study is to demonstrate the applicability of the AM process to the fabrication of large structures by manufacturing the excavator cabin using the AM process. characteristics and specifications of real cabin were considered and redesigned as a part for 3D printing by applying DfAM, and Physical printing was performed using LOAM which can rapidly fabricate large structure. At the same time, AM's direct fabrication can save considerable time and cost by replacing the main process required for cabin manufacturing.

This study can be used as a methodology when creating final products through new project, product development, using 3D printing technology, etc. In order to make a 3D printed product by applying DfAM, it is necessary to understand precisely characteristics and purpose of the object to be created. This allows selection and application of appropriate design techniques in the design process. For real production, AM process selection is needed considering object characteristics and purpose. In order to choose a proper AM process selection, the characteristics and limitations of AM to be used should be considered. After AM process selection, identify the elements that interfere with the actual production and completion, or take into account the new requested parts of the client or designer, and the process should be proceed of mutual correction through feedback to finalize the final design. Once the final design has been decided, begin actual production. At the same time, assembly and post-processing are discussed and combined with the conventional process. Figure 46 is shown the process flow for production of 3D printed products using DfAM.

The use of LOAM allows rapid prototyping of large-sized structure and the limitations of AM technology in real industry will no longer be a problem. Over time, LOAM's technology development will produce larger, higher quality products. However, the technical limitations of LOAM need to be supplemented. It is necessary to improve the limited design complexity as generating supporter from the present situation in which the non-supporter shape must be maintained. In order to produce smooth parts, need improved toolpath generator of slicing software. Further research is needed. LOAM has a rougher surface quality than other AM processes, making post-process is very difficult. In order to solve rough surface quality, it is necessary to discuss a combining system with conventional processes. Therefore, we will study the development of product quality by using a system combining LOAM and conventional process as a future work.

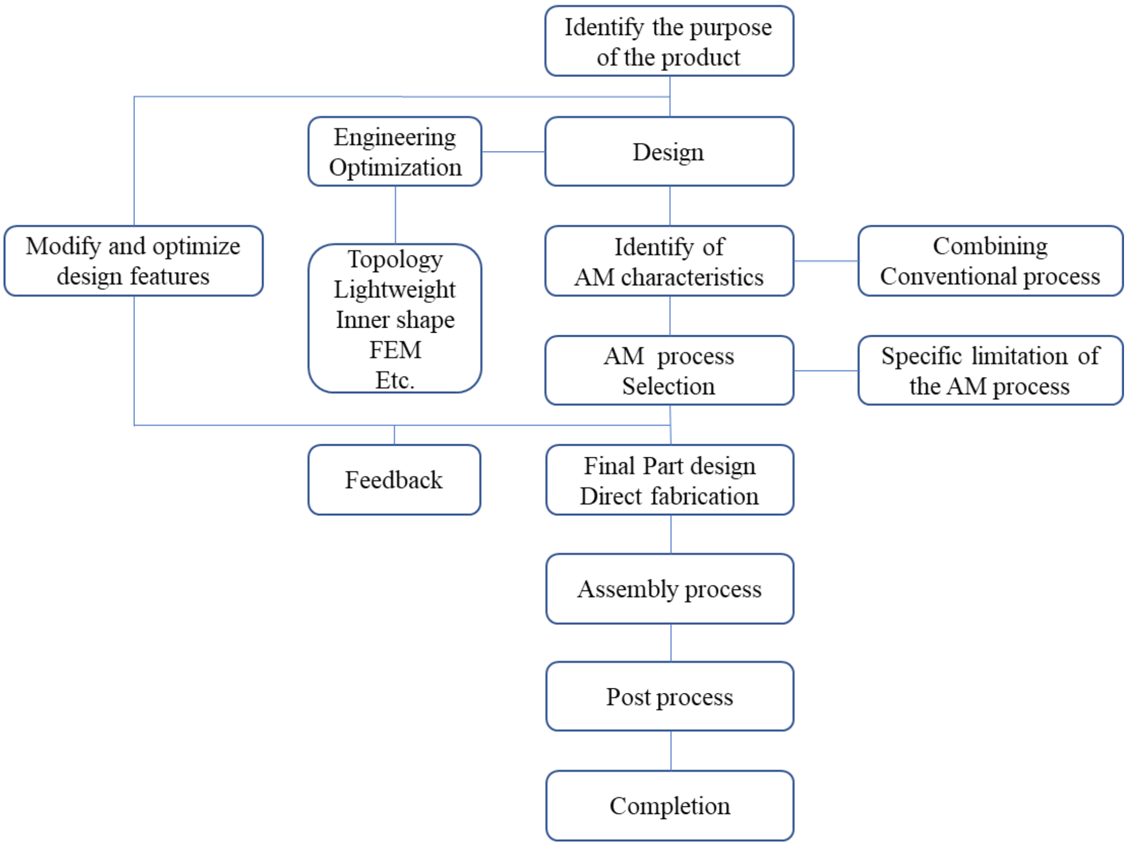



**Figure 46 DfAM process for Large Object Additive Manufacturing**

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